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Modular Open-Source Toolbox for Optics Education

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Ing. Barbora MARŠÍKOVÁ

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GUTACHTER

1. **Prof. Dr. rer. nat. Rainer Heintzmann**, Institut für Physikalische Chemie (IPC), Friedrich-Schiller-Universität Jena, Helmholtzweg 4, 07743 Jena und Leibniz-Institut für Photonische Technologien (IPHT), Albert-Einstein-Straße 9, 07745 Jena
2. **Prof. Dr.-Ing. Timo Mappes**, Deutsches Optisches Museum, Carl-Zeiss-Platz 12, 07743 Jena
3. **Prof. Dr. Katrin Heinze**, Rudolf-Virchow-Zentrum - Center for Integrative and Translational Bioimaging, Josef-Schneider-Straße 2, 97080 Würzburg

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'Leave this world a little better than you found it.'

Lord Robert Baden-Powell, founder of the Scout-Movement

'If you can't explain it to a six year old, you don't understand it yourself.'

Albert Einstein

Zusammenfassung

UC2 ist eine modulare quelloffene Toolbox für die Erstellung von Hardware-Projekten mit optischen Funktionsblöcken. Es schlägt eine Brücke zwischen Bildung und Wissenschaft, indem es eine Alternative zu den Standardwerkzeugen bietet, einen generischen Werkzeugkasten, der für beide Bereiche verwendet werden kann. Die gleiche Basishardware soll dazu dienen, Photonik und ihre Anwendungen auf interaktive Weise zu lehren, und die Schüler können das gleiche System später in ihrer eigenen Arbeit für das Prototyping verwenden.

Als gemeinschaftliches Projekt profitiert UC2 von den Erfahrungen der ersten Anwender und von seiner Attraktivität für projektbasierte Kurse. Es ist eine kollektive Anstrengung von vielen Forschern und Studenten. Die vorliegende Arbeit zeigt die Beiträge der Autorin zu diesem Projekt.

In dieser Arbeit stellen wir die Entwicklung und Erprobung der Hardware für die Bildungsanwendungen vor. Die wichtigsten Erkenntnisse des Open-Source-Hardware-Designs werden bewertet und in einer Entscheidungsmatrix zusammengefasst, die Randbedingungen für die Entwicklung vorgibt. Besonderer Wert wird auf die Verbesserung der Zugänglichkeit des Werkzeugkastens gelegt, indem eine umfassende Dokumentation bereitgestellt und die Einstiegshürde gesenkt wird.

Es wurden vier verschiedene Lernkits entwickelt, die zusammenfassend als "TheBOX" bezeichnet werden, wobei sich die MiniBOX im Stadium eines produktionsreifen Prototyps befindet, der für die Massenproduktion optimiert ist. Bei den BOXen handelt es sich um umfassende Werkzeugkästen, die auf ein bestimmtes Bildungsniveau oder die Demonstration bestimmter Experimente ausgerichtet sind. Sie stellen eine kostengünstige Alternative zu den kommerziell erhältlichen Systemen mit niedrigem Einstiegsniveau dar und schaffen eine einladende Umgebung für den wissenschaftlichen Unterricht. Die Entwicklung erfolgte in engem Kontakt mit den Benutzern und die Verbesserungen basierten auf iterativ gewonnenem Feedback. Das System wurde in vielen Workshops und Kursen getestet und fungierte als Werkzeug für Schülerprojekte.

Abstract

UC2 is an open-source modular toolbox for making hardware projects based on functional optical blocks. It creates a bridge between education and science by offering an alternative to the standard tools, a generic toolbox that can be used for both fields. The same basic hardware is meant to be used for teaching photonics and its applications in an interactive way and the students could later use the same system in their own work for prototyping.

As a community-driven collaborative project, UC2 benefits from the experience of its early adopters and from its attractiveness for project-based courses. It is a collective effort of many researchers and students. This thesis shows the contributions of the author to the project.

In this work, we present the development and testing of the hardware for the educational applications. The key aspects of open-source hardware design are evaluated and summarized into a decision matrix defining the boundary conditions of the development. Special importance is given to improving accessibility of the toolbox by providing comprehensive documentation and lowering the entry barrier.

Four different educational kits, in summary called “TheBOX”, were developed, with the MiniBOX being at the stage of a production-ready prototype, optimized for mass production. The BOXes are comprehensive toolkits aimed at a specific education level or demonstration of certain experiments. These present a low-cost alternative to the commercially available systems. Additionally to the advantage in price, they offer a lower entry level and create an inviting environment for science education. They were developed in close contact with the users and the improvements were based on iteratively acquired feedback. The system was tested in many workshops and courses and provided tools for student projects.

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Ehrenwörtliche Erklärung

Ich erkläre hiermit ehrenwörtlich, dass ich die vorliegende Arbeit selbständig, ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel und Literatur angefertigt habe. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet. Bei der Auswahl und Auswertung folgenden Materials haben mir die nachstehend aufgeführten Personen in der jeweils beschriebenen Weise unentgeltlich geholfen:

1. Eda Bingöl arbeitete unter meiner Aufsicht an den alternativen Baustein-Designs in Abschnitt 3.4 und der PolarBOX in Abschnitt 4.1.3. Sie entwickelte, testete und dokumentierte die in diesen Abschnitten beschriebenen Designs.
2. Teile der Arbeit in Abschnitt 4.2.2 wurden von den Gymnasiasten während ihrer Seminarfacharbeit unter meiner Aufsicht angefertigt. Der Umfang ihrer Arbeit ist in diesem Abschnitt ausführlich beschrieben.
3. Die grafische Gestaltung der MiniBOX-Broschüre im Anhang B wurde von Katrin Uhlig aus der ÖA-Abteilung des Leibniz-IPHT übernommen.

Weitere Personen waren an der inhaltlich-materiellen Erstellung der vorliegenden Arbeit nicht beteiligt. Insbesondere habe ich hierfür nicht die entgeltliche Hilfe von Vermittlungs- bzw. Beratungsdiensten (Promotionsberater oder andere Personen) in Anspruch genommen. Niemand hat von mir unmittelbar oder mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen.

Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Die geltende Promotionsordnung der Physikalisch-Astronomischen Fakultät ist mir bekannt.

Ich versichere ehrenwörtlich, dass ich nach bestem Wissen die reine Wahrheit gesagt und nichts verschwiegen habe.

Jena, den

.....

Unterschrift der Verfasserin

List of Abbreviations

3D	Three-dimensional
3DP	3D-printed
ABS	Acrylonitrile Butadiene Styrene
ASA	Acrylic Styrene Acrylonitrile
BOM	Bill of Materials
CAD	Computer-Aided Designs
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CC-BY	Creative Commons - by attribution
CE	conformité européenne, French for European conformity
CERN	European Organization for Nuclear Research
CNC	Computer Numerical Control
COVID-19	Coronavirus Disease 2019
CZG	Carl-Zeiss-Gymnasium
DIY	Do-it-Yourself
FDM	Fused Deposition Modeling
FSU	West
GDNÄ	Gesellschaft Deutscher Naturforscher und Ärzte
GNU	GNU is not Unix!, recursive acronym
GUI	Graphical User Interface
HRW	Hochschule Ruhr
IM	Injection-moulded
IPHT	Institut of Photonic Technology
KLG	Königin-Luise-Gymnasium
LC	Laser cut
LED	Light-emitting Diode
LSFM	Light Sheet Fluorescent Microscopy
MDK	Modular Developer Kit
MINT	Mathematik, Informatik, Naturwissenschaft, Technik
MIT	Massachusetts Institute of Technology
MOOCs	Massive Open Online Course
MPI-CBG	Max Planck Institute of Molecular Cell Biology and Genetics

NSF	National Science Foundation
ÖA	Öffentlichkeitsarbeit
OER	Open Education Resources
OSHW	Open Source Hardware
OSHWA	Open Source Hardware Association
OSI	Open Source Initiative
P21	Partnership for 21 st Century Skills
PETG	Polyethylene Terephthalate modified with Glycol
PLA	Polylactic acid
PU	Polyurethane
SFZ	Schülerforschungszentren
SPIM	Selective Plane Illumination Microscopy
STEAM	Science, Technology, Engineering, Arts, Mathematics
STEM	Science, Technology, Engineering, Mathematics
STIFT	Stiftung für Technologie, Innovation und Forschung Thüringen
TiM	Trends in Microscopy
UC2	You. See. Too.
UK	United Kingdom
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America
WHO	World Health Organization
WWU	Westfälische Wilhelms-Universität

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Chapter 1

Introduction

Optical microscopy is an essential tool for research in biology, biochemistry, medicine, and other fields. The recent development yielded microscopes with great performance in terms of resolution, contrast, image acquisition speed, and there are many different techniques tailored to their specific applications. However, the advance comes at the cost of increased complexity and price of those devices. The UC2 (You. See. Too.) toolbox presented here was invented to provide an alternative that finds a balance between performance and complexity. With its simple approach, the toolbox also offered new options for teaching microscopy methods and optics in general.

UC2 is a community-driven collaborative project and the input from the users is as important as the development itself. The project is developed by the core team composed of the project founders, Dr. Benedict Diederich and M.Sc. René Lachmann, and myself, but sometimes also with the help of students, colleagues, and collaborators who support us with ideas, testing, and more. Those who gave a particular input for this thesis are mentioned in the acknowledgments or in the respective sections. My contributions are pinpointed in chapters 3 and 4. The UC2 toolbox or its parts were already published and presented in peer-reviewed articles [1, 2], conference proceedings [3, 4], a magazine article [5], and the doctoral thesis of Benedict Diederich [6]. The open-source documentation is available at [7].

This thesis documents the development of the educational branch of the UC2 project. It is an example of engineering an open-source product, of finding the key features and properties to allow both commercialization and further open-source development. This approach to the development and the design decisions are demonstrated on the case of the UC2 toolbox.

In the beginning, the goals of this thesis are stated. The introduction then explains the motivation of developing the toolbox in compliance with the open-source practices. The background and state of the art of optics education and open microscopy is also provided here.

1.1 Goal of the thesis

The focus of the education branch of the UC2 project lies on the use of the toolbox for educational purposes in a broader sense. Developing equipment in the open-source way allows its tailoring for the applications in both research and education as the end users are invited to contribute with their ideas. With proper community maintenance, the project grows on its own, beyond the imagination of its creators. In order to be inclusive to any potential user, the system has to be well-documented, since documentation is the key point for accessibility. The hardware has to rely on available components that can be not only commercially acquired but easily used and implemented, regardless of application.

For the purposes of STEAM education (Science, Technology, Engineering, Arts, Mathematics), I proposed to develop comprehensive educational kits and support them with assembly guidelines and experiment manuals. They shall be compact and easy to use, such that no extra effort is demanded from the teachers. The aim is to lower the entry barrier and show that science, here in particular optics and microscopy but also the related engineering and programming, does not have to be complicated and exclusive, which motivates the pupils to choose their future career in STEAM fields. In universities, the same toolbox could be used for high-end research and therefore the students are directly trained with the technology they can use in the future. My hypothesis is that when the tools are made available, affordable and accessible, non-professional users lose the fear of using them and can even develop them further for their own purposes. This encourages interdisciplinary research and growth in science and technology and therefore it became one of the foci of this work.

The goals can be summarized as lowering the entry level of optics and microscopy by:

- structuring the UC2 project to increase reproducibility,
- providing a comprehensive documentation,
- and designing ready-to-use education kits.

The potential challenges lie in the hardware design and in choosing a suitable approach and testing it in the educational context. The tested and evaluated solutions are discussed in this thesis.

Furthermore, the thesis is written in a simple language to make the text easier to read for a broader audience. Maybe someone finds it inspirational.

1.2 State of the art

1.2.1 Open source in science and education

The Open Knowledge Foundation [8] states that “Open means anyone can freely access, use, modify, and share for any purpose (subject, at most, to requirements that preserve provenance and openness),” [9] which is known as the Open Definition. It is a trend in many fields of human doings to “go open”.

This trend can be traced back to the software development. Early on, software was freely distributed with the hardware of computers. As the development of software became more important and also more demanding in time and financial resources, the companies started to release their software as proprietary, to “close” it by not sharing the source code and distributing only executable machine code. This was an unpopular step among the hackers and programmers, who could no longer study and modify the programs. Considering this ethically wrong, Richard Stallman started the GNU Project (a recursive acronym meaning “GNU is not Unix!”, the proprietary operating system that he wanted to provide replacement for) and founded the Free Software Foundation in 1980s to allow people using computers with free software [10]. He also invented copyleft, the opposite of copyright, as a way to license free software as intellectual property while allowing the users to distribute and modify it. The first complete operating system was Linux and among its distributions the Debian GNU/Linux is worth mentioning for its commitment to the principles of free software. The developers expressed these principles in the Debian Social Contract [11] that became the base of all the later definitions of all the open source movements.

The term “free software” was not considered ideal, because it confused the new users by seemingly focusing only on the price. In 1998, after the announcement of the release of the Netscape browser source code, a strategy session was held as this was seen as an opportunity to educate and advocate for the superiority of an open development process. During this session, the term “open source” was introduced and open-source software soon became adopted by the community [12]. Open Source Initiative (OSI) was founded later that year by Eric Raymond and Bruce Perens [13]. The Open Source Definition was created, derived from the original Debian Social Contract [14]. One year earlier, Bruce Perens also launched the Open Hardware Certification Program with the goal to allow hardware manufacturers to self-certify their products as open [15].

While the development of open-source software went straight ahead with the development of the internet, for open hardware or open-source hardware it was not that simple. Open-source hardware refers to design specifications of a physical object, which are licensed in a way compliant with the definition of open. The “source code” of the hardware, meaning schemes, blueprints, and Computer-Aided Designs (CAD), is available for study and modification. Furthermore, the components should be preferably easy to obtain [16]. The development of open-source hardware results in production or prototyping and due to that, unlike open-source software, involves monetary investment for materials, although upcycling and the frugal approach is often involved. The movement is managed by the Open Source Hardware Association (OSHWA) since early 2010s and the Open Source Hardware (OSHW) Definition 1.0, tailored from The Open Source Definition, was developed by its members. Only hardware that complies with its criteria, as stated by the Definition [16], is allowed to be distributed as open-source hardware.

Whether it concerns software or hardware and aside of any definitions, the way to open source is described as a set of principles that can be broadly applied to any field, making its products or results accessible. Even though the principles are clear to anyone who is part of the open source community, there is no general consensus on their vocalization. Based on our experience with open source and on [17, 18], for the purposes of this thesis, I define the following three principles:

- **Transparency.** It is in the nature of an open-source project that everyone has access to all the information and materials necessary for its further development. But the transparency of an open-source project goes beyond sharing code and blueprints, it means sharing the good intentions. The contributors must follow this principle and the community observes and inspects every step. All ideas coming from the contributors are welcome and time shows, if a specific feature gets adopted by the community.
- **Community.** A community forms when people unite around a common purpose. In terms of open source, it is not just a community of users, it is one where the users actively participate and give something back. Contributors arise from participants, who all started as users. The project grows by the input and feedback of the community, building upon each other’s ideas. The entry barrier has to be low to create a welcoming environment.

- **Collaboration.** Working together is more efficient than working alone and being able to modify the work of others opens new possibilities. Collaboration is the advanced level of participation, it is helping others because it helps the project and enhances its usefulness in a process of continuous improvement.

The demand for openness has infiltrated most fields by now. One of them is open education [19]. The OSHWA has defined education of science and technology through the use of open-source hardware as one of its main purposes [20]. Briefly, open education describes efforts to expand access to education, improve its quality, increase its affordability, and foster collaboration and sharing through co-creation of educational materials and the freedom to use, customize, improve, and redistribute them. Nowadays, the Open Education Global [21] supports its development and its areas of focus such as Open Education Resources (OER), Massive Open Online Courses (MOOCs) but also Open Access, Open Data and Open Science. OER include any kind of educational or teaching materials, including hardware. By demanding increased access to knowledge, open education is closely linked to open science via open access [22], which is a term that refers to the practice of making peer-reviewed scholarly research and literature freely available online to anyone interested in reading it. Open Access dates back to 1991 when the archive arXiv.org [23] was founded for physics pre-prints. After a crisis in 1990s when scientific literature was difficult to obtain due to increasing prices of journals, the open access movement was formally introduced and defined in several declarations by the Budapest Open Access Initiative, the Bethesda Statement on Open Access Publishing, and the Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities.

Science can be seen both as good and bad example of open-source practices. Open science began arguably in 1600s when the first scientific journals started to publish discoveries and inventions, offering the results for review and reproduction by the community [24]. The quality of the journals was overseen by learned societies such as the Royal Society and it was stated that all theories are open to being questioned and stated results must be repeatable. As the academic environment grew more competitive and the pressure on publishing in renown journals increased, it became common to present the results in a way that proves their reliability but prevents the experiments from being repeated by anyone who was not a part of the original research. Additionally, by the end of the 20th century the language of the journals became so complicated that they were inaccessible for a layman [25]. The pressure on making science open

increased with the demand for open access and nowadays open science is internationally recognized and seen as preferred. Recently, under the pressure of the COVID-19 pandemic, the World Health Organization (WHO), the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the United Nations High Commissioner for Human Rights joined in an appeal [26] to reaffirm the fundamental right to enjoy the benefits of scientific progress and its applications and advocate for open, inclusive and collaborative science. UNESCO prepares their Recommendation on Open Science [27], which shall be adopted by researchers in all fields and not only in the pandemic-related research.

Countless initiatives and efforts work towards open-source software and hardware, open science, open access, open education and opening of other fields. There seems to be a consensus that “open” is the direction to go. However, the level of openness varies especially in the open-science and open-hardware communities and there is no standard yet of how open should open science and open hardware be.

There are of course disadvantages of this approach. Being open-source always presents the risk that the ideas might be stolen, the hardware reproduced, behind the author’s back, and there is no legal way to prevent this from happening. For this reason, most countries still see patents as the best way to protect know-how and an open-source project is viewed as a risky investment. However, we prefer to advocate the benefits.

1.2.2 Open Microscopy

Light microscopy is a field that provides the possibility of new discoveries for more than 300 years. Especially in the last century, the methods advanced due to implementation of new technologies, enabling seeing single molecules or living organisms [28]. But along with the technical progress, the equipment became expensive and complicated and therefore the top-end research that relies on such tools is reserved for well-funded research institutions in first-world countries. The open-source spirit infiltrated science a few decades ago, but only in terms of open-access journals or open source software and data analysis. The physical equipment necessary to perform experiments remained exclusive, mostly for monetary reasons related to manufacturing [29, 30].

Open-source hardware is the chance to revolutionize this aspect [31]. Open hardware designs came in use especially as 3D-printers have become an increasingly common item of equipment within research laboratories, enabling easy prototyping. There is a growing number of established open microscopy

projects that rely on 3D-printing, such as the OpenFlexure microscope from the Bowman lab [32], the 100€ lab [33], and others [34–38]. Since the stability of 3D-printed parts is limited, for more advanced methods such as light sheet microscopy the scientists chose the approach to employ commercially available components but documented their system in a way that is easily reproducible [39, 40]. Others build their system based on the versatile building kit Lego®[41, 42]. The projects commonly use programmable electronics and mini-computers, which are affordable and partially open-source [43, 44]. Many of the projects find themselves on the border between research and education, as the accessibility of the equipment yields in their attractiveness for outreach [45].

The open microscopy community is a supportive worldwide network where ideas come to life but an open standard is missing, as the makers typically start by developing a tool to help them answer their specific scientific question. Many of the projects are also still too complex to be adopted by broader audience, such as biologists with no technical training, and too expensive to provide a solution for low-budget applications.

1.2.3 UC2 toolbox

UC2 (You. See. Too.), as usually presented is “a general-purpose modular framework for making interactive (electro)-optical projects” [7]. The project started in 2017 and arose from a collaboration on developing a compact microscope that fits inside an incubator. Due to the availability of tools and the need for easy and fast manufacturing, 3D-printing was the method of choice for rapid prototyping of this device.

Early development

The early versions of the Incubator-enclosed Microscope are shown in Fig. 1.1. The following analysis of the first stages of the project explains the design decisions on which the later work is based.

The initial idea was to design a 3D-printable monolithic microscope (see Fig. 1.1a), with a small spatial footprint. This required reinventing the wheel for each design update and 3D-printing and building the whole microscope after every improvement. Therefore, modularity was chosen as a key feature of the system. A modular design had the advantage that simple modules, holding passive components like mirrors, could be kept while the more complex focusing mechanism was iteratively improved. When switching to the

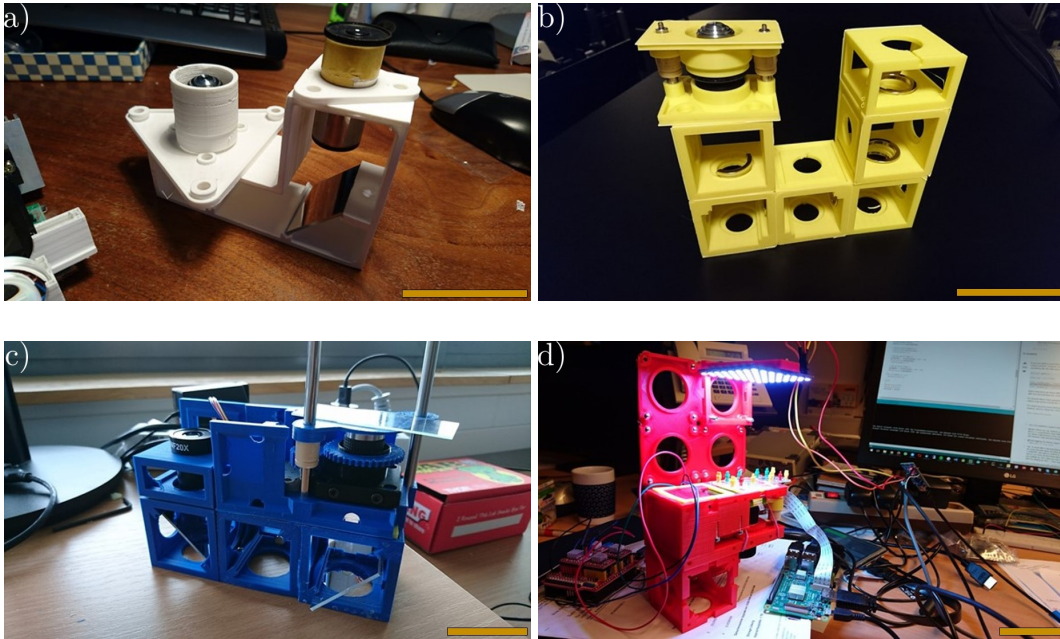


FIGURE 1.1: The early development of the Incubator-enclosed Microscope (05-08/2017). a) Monolithic microscope. b) First modular system of cubes connected via magnets. c) Modular microscope with a baseplate. d) Modular microscope with a baseplate, the attachment is provided by ball magnets and screws. Scale bars: 50 mm, personal project documentation, B. Diederich [6].

modular system, it was decided to match the module size to align with the theoretical principles of microscopy, to follow the so-called 4F system, which is an application of the theory of Fourier optics. The lenses are aligned in a way that focal planes of consecutive elements coincide and enable predicting the system behavior mathematically [46]. The analysis of many available optical components, imaging systems, and frameworks resulted into the choice of a design pitch of $d_{\text{block}} = 50 \text{ mm}$ that optimally balances compatibility, handling, and flexibility, and it enables 4F setups using lenses with commonly manufactured focal lengths [1]. In ideal case, lenses with F-to-F distance of $n \times 100 \text{ mm}$ should be used, but such lenses are not commercially available.

In the first modular system, Fig. 1.1b, the modules (3D-printed cubes) are placed next to each other and joined together by the force of magnetic rings. There were two issues: these rings were fragile and broke easily and this building principle still requires the microscope to be disassembled in order to exchange a module on the bottom. Additionally, due to the 3D-printing accuracy, the cubes were not always precisely aligned on a shared axis when assembled. Therefore, the concept of the “baseplate” was introduced (behind the cubes in Fig. 1.1c), to which the modules attach. It serves as a backbone of the microscope, providing stability. Magnetic connection between the

modules and the baseplate was satisfactory but the fragile rings were replaced by a self-aligning mechanism of hexagon socket head screws sitting on ball magnets, resulting in the system shown in Fig. 1.1d.

The assembly principle of a setup was reliable for the state of development. But the way in which the modules were printed and built posed an issue. The cubes were printed in one piece, which simplified the assembly, but limited the freedom to create protrusions or grooves that would hold an external component.

With the toolbox being modular, other setups than just the Incubator-enclosed Microscope could be built easily and developed in parallel. The Abbe Diffraction Experiment [47] and Michelson Interferometer [48] were the first ones tested. The 3D-printed modules, due to the click-on way of building a setup and due to being colourful, as various filaments were used, also attracted attention for the application in outreach and they were first used for this purpose during the Girls in Science Day in April 2018.

The project was named UC2 (suggesting that you, the user, could see too when using the toolbox) and the first open-source version was released on 18th of August 2018 in a GitHub repository [7]. The hardware was licensed under the CERN Open Hardware License v1.2 (a license used in open-source hardware projects created by CERN, the European Organization for Nuclear Research) [49] and the software under the MIT License (a permissive free software license originating at the Massachusetts Institute of Technology) [50]. All the documentation is published as CC-BY (Creative Commons most permissive license, BY stands for "By attribution") [51].

The decision to release the project open-source was influenced by both subjective and objective factors. On one side, the authors felt very inspired by the open-source movement, described in section 1.2.1, as it gives the project the opportunity to be beneficial for a broad spectrum of users. Making the research open-source gives one the freedom to talk about their work, not only results, and ask questions to the scientific community even on social media. There is a growing number of projects that choose this path and they form a welcoming environment where ideas are shared and researchers supported. In modern science it is probable that when you have an idea, someone already considered it, and when the ideas are shared publicly, it is very easy to build on the efforts of another researcher or even a tinkerer who might be on the other side of the world. From the practical point of view, having your idea patented costs time and money and gives you limited freedom of what you can do with your own results. Nevertheless, the options to have the UC2 system patented

were examined but it was found that the idea of a modular microscope is not specific and unique enough for the patent definitions (B. Diederich, personal communication, 24th of April 2021). The great goal of the UC2 project is to become an open standard for microscopy [1] and make the field available, accessible, and affordable for a broad audience.

I have joined the project in October 2018 and was a part of the further development, working mainly on the educational applications, and my own designs and contributions will be described in the following chapters.

Today, the UC2 toolbox accommodates over thirty modules and about twenty documented applications [7]. Many of them find their use in research, but this thesis focuses on those used in education. Regardless of application, the project remains completely open-source. The entry barrier is lowered by means described in the following chapters, such as enforcing a comprehensive documentation, organizing workshops and supporting other groups on developing their projects based on the UC2 platform.

Basic module properties

Before the initial release, the 3D-printed module was improved for assembling it with external parts by a design decision to split it in two parts. The cube was separated into a base (a body of the cube) and a lid, see Fig. 1.2. This simplified printing using standard 3D-printers working on the fused deposition modeling (FDM) principle. Furthermore, it allowed keeping the cube fully universal and giving it a function by easily inserting components as plug-ins [1]. The cube version v0 was derived from the standard one inch cage system, used by Thorlabs, Inc. or Edmund Optics Inc., and it was therefore compatible with their lens mounts and other parts and allowed sliding the component within the cube. This design required the implementation

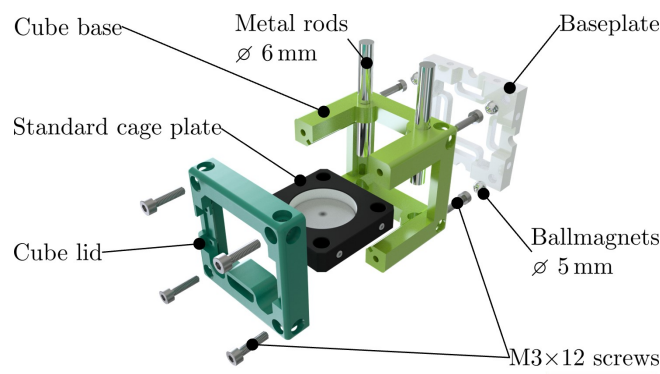


FIGURE 1.2: Scheme of the modular principle, version v0 of the system.
Scale bar: 50 mm.

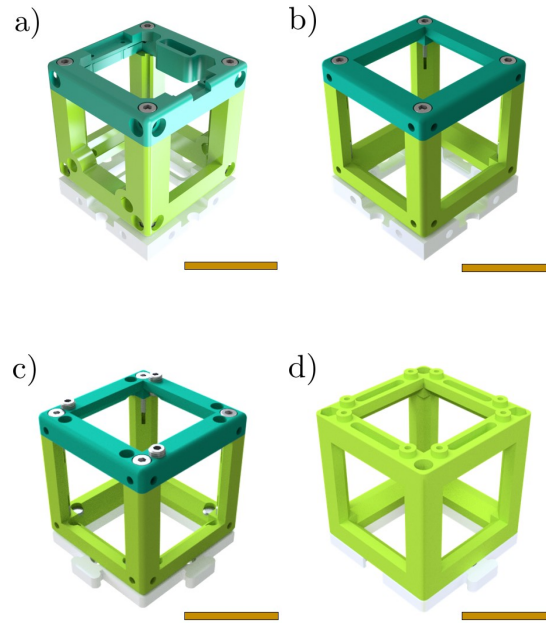


FIGURE 1.3: Version history of the basic module. a) Cube v0, relying on metal rods or tailored inserts. b) Cube v2, center-symmetric. c) Cube v3, compatible with injection-moulded cubes and using baseplate puzzles. d) Injection-moulded cube. Scale bars: 50 mm. [7]

of two 50 mm long metal rods with the diameter of 6 mm in each lens cube. Other modules, like the cube housing a Raspberry Pi camera, worked on the principle of sliding the 3D-printed insert into matching slots in the edges of the cube. Some of the modules, namely the Z-stage, which enables focusing an objective by moving it along its optical axis, and the LED cube, which provides illumination using an LED matrix, included electronic control and the lid had a slot for housing the Arduino Nano microcontroller board. The cube and the lid were very robust, which led to long printing times and limited space for inserts.

The cube v0 (Fig. 1.3a) suffered from plenty of disadvantages, such as the long printing time and the need for metal rods. Regarding the electronics, the Arduino Nano was replaced by the ESP32 microcontroller from Espressif Systems, because it supports WiFi connection, but it could not fit in the the lid, making the electronics-housing slots redundant. The attempts to improve the design of the building block converged to the cube v2 (Fig. 1.3b). No version v1 was defined due to a mistake in the naming convention. The cube became symmetric with respect to the center planes between each pair of opposite faces, therefore the inserts could be placed either parallel or perpendicular with respect to the lid, with no need for rods or any other mounting structure. Two generic types of inserts were introduced, the perpendicular and the

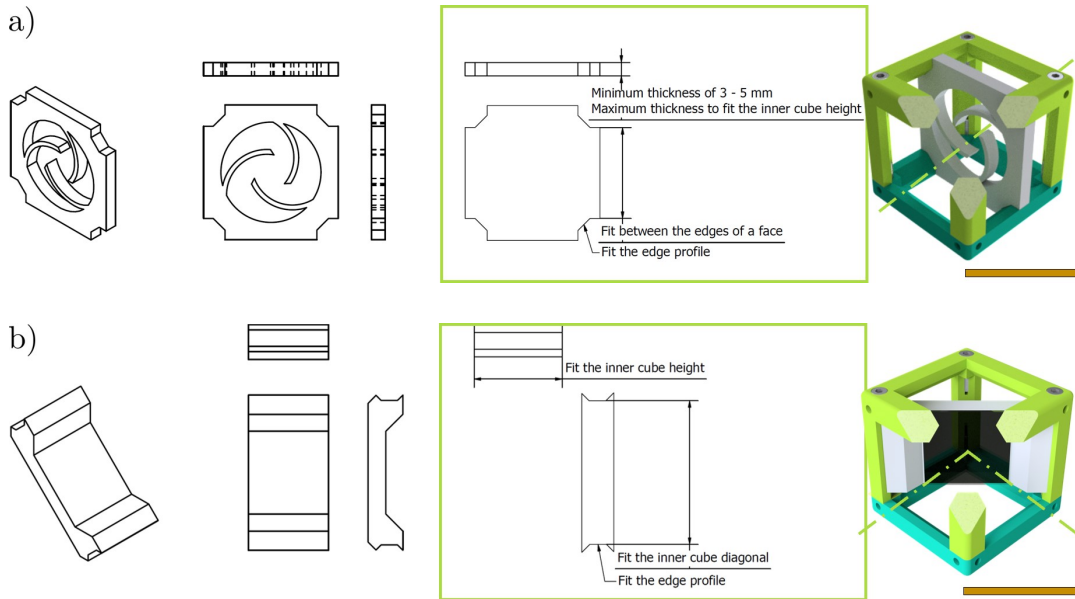


FIGURE 1.4: The concept of the insert used in version v2 and higher. a) Perpendicular insert - spiral lens holder. b) Diagonal insert - 45°-mirror holder. Scale bars: 50 mm.

diagonal one. This concept, shown in Fig. 1.4, is maintained until the current version. The perpendicular insert is perpendicular to the intended direction of the optical axis, running through the centers of two opposite faces of a cube. The diagonal insert is fixed in an angle of 45° with respect to the optical axis. The cube v2 was slimmer and the printing time decreased by almost 25%, without affecting the stability of an assembled module.

Some of the designs could not be fitted inside a cube, due to size limitations. Therefore, larger modules were implemented, covering a size of two neighboring cubes, referred to as the 2×1 cube, for example to include a Z-stage. In other cases, such as the LED matrix, the external parts were mounted using a tailored module, which was not cube-shaped.

The UC2 cube v3 (Fig. 1.3c) was introduced together with the injection-moulded (IM) cube (Fig. 1.3d). Their properties are described in detail in section 2.2.3 and the cube v3 is depicted in the technical drawings in appendix A. The cube v3 is in fact only an adaptation of the cube v2 for compatibility with the IM cube. There is a difference in the range of 0.1 – 0.3 mm in the inner dimensions between v2 and IM cube, thus, the outer cube and the inserts had to be adapted to that. In the project documentation, the v3 cubes are distinguished as 3DP cube (3D-printed) and IM cube.

The baseplate remained without major changes from v0 to v2. It was composed of baseplate units that were assembled in the Computer-Aided

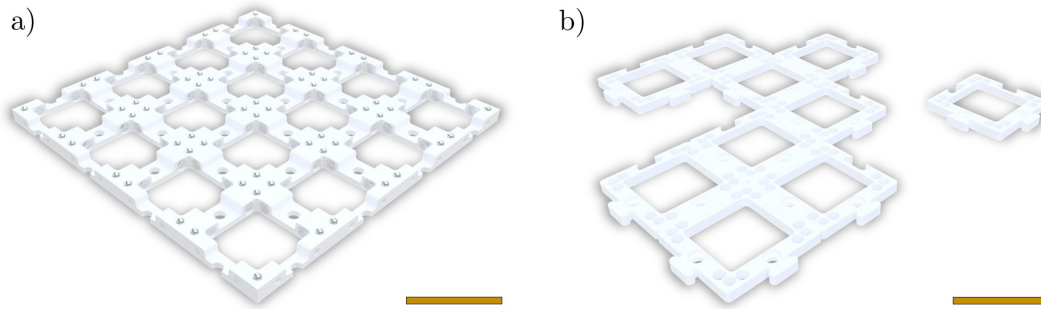


FIGURE 1.5: The modular baseplate. a) Monolithically-printed $4a \times 4$ baseplate used in v0 and v2. b) Puzzle baseplate used in v3 and injection-moulded system. Scale bars: 50 mm.

Design (CAD) software into a baseplate of a chosen size, typically 4×4 units, 4×2 or 4×1 , and then it was printed in a single piece. The 4×4 baseplate, which is the biggest one possible for most common 3D-printers, is exemplary shown in Fig. 1.5a. The baseplates could be connected into larger ones via holes in their sides, using screws, but this yielded limited stability. For the design of the IM baseplate, hence baseplate v3, a more modular solution was needed (for details about the decision criteria see section 2.2.3) and a puzzle system was selected, shown in Fig. 1.5b. This system is explained in detail in section 2.2.3.

1.2.4 STEAM education in Optics

The abbreviation “STEM” stands for the fields of Science, Technology, Engineering and Mathematics (in Germany it is called MINT - Mathematik, Informatik, Naturwissenschaft, Technik). It typically includes educational activities across all grade levels, from pre-school to post-doctorate, in both formal (classrooms) and informal (afterschool programs) environments. The term got adopted and wide-spread by the American National Science Foundation (NSF) in early 2000s, although it was used by other organizations even before that. The NSF identified these fields as crucial for the economic growth of the country and realized that in order to succeed in these disciplines, it is important to prepare the children for future jobs in those [52]. Soon, STEM became a buzzword in education worldwide, although it is not always clear what methods and practices are meant by that. Generally, it is a curriculum based on the idea of educating students in these fields in an interdisciplinary and applied approach. More recently the term STEAM is used, which includes

Arts as well, highlighting the importance of creativity in learning the STEM disciplines.

STEAM is often described as education for the 21st century skills. These can be seen as abilities and dispositions required for success in this century. There are again many definitions of what STEAM education should focus on but I choose to mention the one of the Partnership for 21st Century Skills (P21) [53] established in 2002, because the four listed skills resemble the common goals and principles of the open source movement (section 1.2.1), explaining why open education is often mentioned in this context. There are the Four Cs: *Critical Thinking and Problem Solving, Communication, Collaboration, Creativity and Innovation*.

The interest in STEAM education gave a rise to many projects and courses. At the same time, the growth of open-source and accessible technology provides these with tools. Two projects are named here, as they are an inspiration for UC2. Their story is described as found in their respective cited websites.

First of them is the Arduino [43], an open-source electronics platform based on accessible hardware and software. It started at the Ivrea Interaction Design Institute in Italy in 2005 as an easy tool for fast prototyping, aimed at students without a background in electronics and programming. Before that, electronics was a field reserved for the trained experts, the development of prototypes was slow and the success uncertain. Arduino is easy-to-use for beginners, yet flexible enough for advanced users, therefore it helps a large variety of users to build their own projects. Teachers and students use it to build low cost scientific instruments, to prove chemistry and physics principles, or to get started with programming and robotics. The Arduino Education creates STEAM programs that support students on their learning journey through middle school, high school, and university. There is also an active community of users that further improve the hardware and software and share their ideas.

In the field of Optics, there is the Foldscope [54], an extremely durable and portable paper microscope. Although not fully open-source, as they do not share original design files, the inventors describe it as “ultra-affordable”, because all the necessary parts for one microscope may cost as little as 1\$. It was invented by Manu Prakash and Jim Cybulski at the Stanford University, who, during their field visits around the world, encountered the problem of bulky, broken microscopes, or a lack of microscopes entirely. They asked themselves the question “What is the best microscope you can build for under

1\$ in parts?” and found the answer for it. The Foldscope Instruments Inc. company was founded in 2015, to scale the production above the possibilities of a research institution, and by 2019 there was one million of Foldscoopes distributed worldwide. They also maintain a community called Microcosmos, to connect their users and allow them to share their discoveries. With the global distribution, the users contributed with a diversity of applications. Due to low price, the Foldscope found an important place in schools in rural areas of India and South America, where there was previously little to no STEAM education.

In the schools of Germany and other European countries, the syllabus often remains the same for past decades. STEAM education mostly comes in the form of project-based courses by the initiative of enthusiastic teachers and from extracurricular education centers. The standardized equipment is provided by a few stable vendors and innovation on large scale is a slow process.

With respect to experimental equipment for the education of optics we mention two commercially available systems. There are the “Class Set Optics” and the “PROFI Optics” from the German company fischertechnik GmbH [55], a partially modular building kit that offers products for education as well as toys. The Class set Optics offers six experiments in sixteen sets (meant for one teacher and thirty pupils working in pairs) for the price of circa 1,000€. The PROFi Optics set offers 15 advanced models for the price of circa 90€. For higher level education, there is the Thorlabs Discovery product line from Thorlabs, Inc [56]. Their “Optical Microscopy Course Educational Kit” provides easy-to-use equipment and educational materials for a complete course, the price of one set is close to 10,000€. Additionally, they offer smaller sets for specialized experiments, such as Michelson Interferometer, Polarization, or Spectrometer. These products are a potential concurrence to their UC2 alternatives described in section 4.1.

Chapter 2

Design criteria

In this chapter a summary is presented, of the conditions and criteria for the development of a toolbox that opens the field of optics and microscopy to a broader audience. The options in terms of available methods and equipment are discussed here and, in the end, the crucial aspects that the toolbox has to fulfill for its various applications, are summarized in a matrix. The criteria were evaluated by the core developers, based on experience and feedback of the audience.

2.1 Boundary conditions in open microscopy and education

Challenge: Fit the toolbox for three types of application: open-source project, research, and education

Solution: Use a decision matrix to assign the conditions to the applications based on their validity. See section 2.4

The aspects covered in this section come from our close collaboration and the development of the tools together with the users. The term “users” broadly refers to all the target groups, including end users (those who wish to use it but do not want to know any technical details), collaborators, contributors, and participants in testing.

UC2 started as an alternative for research areas where the commercially available solutions do not provide the right equipment to fulfill the needs or they are unaffordable due to their price. As such, we initially considered the criteria that apply in the field of Open Microscopy as interpreted from the literature cited in section 1.2.2 and personal communication with some of the authors. The overview is in the following list:

- **Audience:** There are two different groups interested in Open Microscopy. The end users, typically biologists, need an easy-to-use complete device, while the community of potential developers, often referred to as “tinkerers”, needs access to all hardware and software and the ability to modify them. An open-source microscopy project has to consider both of them.
- **Performance:** The system has to fulfill the needs of the users, by providing them with access to a tool or method, sufficient in the key parameters. Any lack in performance in some aspects must be justified by the price, small footprint, portability. This is specified by the concrete application.
- **Availability:** The system can be build using commercially available components and manufacturing methods such as 3D-printing, which are nowadays common in universities, research institutions, but also at homes. The system potentially provides access to novel methods that are not present in any commercial device, due to the tedious process of patenting, production, and marketing a product.
- **Accessibility:** Detailed, clear, understandable, well-structured, and complete documentation must be provided for reproducing and using the system, including the original design files.
- **Affordability:** The system must be cost-efficient. The open-source microscopes are usually the cheaper option when implementing the same method, compared to commercial systems. But the price rarely considers the time that the developer spent on designing it and the time the user spends on reproducing it. The system does not have to be cheap in a broad sense, meaning that it is not the aim to make the high-end applications affordable for every single person.
- **Adaptability, customization:** It is advantageous to provide an option to tailor the system, even to the end-users or not-so-eager tinkerers.
- **Support:** For successful implementation, the authors of the project should be available for answering questions and troubleshooting.

The increased interest in the UC2 toolbox for education led us first to organize individual workshops and later to consider progressing into this field systematically. However, the criteria for teaching tools are different:

- **Comprehensive toolbox:** Any teaching tool must be provided as a system that works out of the box, without putting an additional burden, like extra costs or preparation time, on the educators.
- **Creative potential:** It is an advantage, if the system offers opportunities for project-based interdisciplinary (STEAM) courses as well.
- **Documentation:** Teaching materials explaining the use of the tool must be provided along. These must target at given education level.
- **Affordability:** Here, low-cost solutions are preferred. Schools and other educational institutions often operate on a tight budget.
- **Low maintenance:** The tools should have a long life time, be robust and cleanable, to support multiple generations of students. A long-lasting system with a higher (but affordable) price is a reasonable investment.
- **Certification:** Any product sold in the European Economic Area must acquire the CE marking (“conformité européenne”, French for “European conformity”), showing it meets high safety, health, and environmental protection requirements, and often also other certifications. Non-certified equipment is only acceptable in small-scale collaboration projects, not for any kind of sale.

With the growth of the project, we identified two further aspect, important for the successful implementation in both of the mentioned fields.

- **Scaling:** When more than a single setup is needed, be it in a classroom or a parallelization of microscopy experiment, the do-it-yourself (DIY) approach is no longer sustainable. While 3D-printing is great for the tinkerers, the production and assembly time has to be reduced in order to bring the toolbox to a broad user base.
- **Commercialization:** Open source is beneficial in the idea sharing, development and open publishing of scientific results. For the end-user however, it is often not possible to recreate an open-source system due to personnel and time limitations. It is preferable to buy a complete solution. The option to customize it, thanks to being open-source, is an advantage.

These factors came from the inquiries from potential users and the feedback from the testing (see section 4.3.1) and together with the practical aspects described in the following sections form the boundaries within which we designed our prototypes.

2.2 Methods and tools

The methods and tools used for the toolbox development were chosen due to their availability to the authors and to the target audience. Other methods of production were not considered since the available methods yielded satisfactory results. Other methods, such as casting or water jet cutting, could still be considered for scaling in the future.

2.2.1 CAD Software

Challenge: Enable professional and open-source development

Solution: Design the toolbox using Autodesk Inventor but provide the basic components designs for openSCAD

Computer-Aided Design (CAD) involves creating computer models defined by geometrical parameters. The software allows the designer to view, alter and test the three-dimensional object using a computer [57]. Often the term is used together with Computer-Aided Manufacturing (CAM), which uses CAD-produced geometrical design data to control automated machinery, and a general abbreviation CAE, which stands for Computer-Aided Engineering.

The hardware parts of the UC2 toolbox are designed in the 3D-CAD software Inventor from Autodesk Inc. [58]. We initially chose Autodesk Inventor because it is a professional-grade software for product design and engineering and at the same time it provides free student licenses for university students with access to all the features. It is commonly used by research institutions and universities but also many companies engaged in hardware development.

However, for the UC2 project there is an issue with Autodesk Inventor. It is a proprietary software. Thus, we explored the open-source alternatives, see the comparison in Table 2.1. The pros and cons of these programs were evaluated and the user experience of the core developers played an important role there. With the aims of the project in mind we chose two of them as long-term solutions.

Autodesk Inventor is too advanced for makers and hobbyist, but it is the best of the tested software for professional engineering and product development. It offers many features for rendering animations, hence product presentation, and it allows the user to create standardized technical drawings. Handling large assemblies is no issue here and Bills-of-Materials can

Software	Autodesk Inventor 2022	Autodesk Fusion360	OpenSCAD 2015.03	FreeCAD-2021 v0.19
License	proprietary, 2,839€ per year, academic license available	proprietary, 494€ per year, free for hobbyists and non-commercial use	open-source, GPL-2.0-or-later	open-source, LGPL-2.0-or-later
Aim	engineering, product design, simulation, documentation	CAE, CAM, 3D-printing, simulation	available CAD designing, 3D-printing	engineering, parametric modelling
Operating system	Windows	Windows, macOS, Android	Windows, macOS, Linux	Windows, macOS, Linux
Principle	2D and 3D data integration with parametric, direct edit and freeform modeling tools	cloud-based 3D modeling platform	script-only-based modeller	3D parametric modeling application, Python compatible
CAD viewer	yes	yes	no	yes
Parametric	yes	yes	yes	yes
Technical drawings	yes	yes, not optimal	no	yes, not the aim
Rendering, animation	yes	yes	basic, no material features	yes, in development

TABLE 2.1: Comparison of tested CAD software.

be exported automatically. Therefore it is optimal for the future professional development of the toolbox, also when it comes to commercialization.

For reproduction of our modules, sharing the *.stl files (Standard Triangle/Tessellation Language) is sufficient. Such file describes only the surface geometry, without any colour or texture, and the surface must be closed to create a volume for 3D-printing. These files can be imported into any slicer, a piece of software that translates a three-dimensional object into layers and

exports a G-code, a set of instructions for a 3D-printer on movements along the axes and extrusion of the material.

In compliance with the open-source principles, we also share the original design files (*.ipt and *.iam from Autodesk Inventor). As the *.stl files cannot be edited and Inventor files rely on proprietary software, to increase the project accessibility in a truly open-source way, we provide the designs of the cube body, cube lid and baseplate, as well as a blank insert in the form of an openSCAD code. Furthermore, openSCAD was used for the parametric designs in section 3.3.

2.2.2 3D-printing

Challenge: Prototyping, stability, reproducibility, tolerancing, life span of the materials

Solution: 3D-printing using PLA for rapid prototyping, other methods for scaling the production (sections 2.2.3 and 2.2.4)

3D printing, or additive manufacturing, is the construction of a three-dimensional object from a CAD model or a digital 3D model [59]. There is a variety of processes that are described as 3D-printing but for the purpose of this thesis we only refer to Fused Deposition Modeling (FDM) [60]. The 3D-printer is instructed via a G-code, a file that contains commands to move the extruder and the printing bed and to extrude the filament. It is a fast way to bring a piece of hardware from design to testing and it became accessible in the last decade. This was the initial method of choice, since it is convenient for rapid prototyping and a 3D-printer was available for the research group. It is also a popular prototyping method in the field of optical microscopy [61].

We experimented with several commonly used 3D-printing materials. Each one has its advantages and disadvantages and it is always necessary to consider the application. The tested materials are compared in Table 2.2. The 3D-printers used for this testing were Prusa i3 MK3S from Prusa Research a.s., Czech Republic, and Ultimaker 2+ from Ultimaker BV, Netherlands. Additionally to the materials, the production costs (3D-printer, electricity, maintenance) need to be considered as well. Except for ABS, the materials were used with the same printer (Prusa) and therefore compare only by the material price. For ABS this poses a disadvantage, as it needs more advanced, hence expensive, printers (Ultimaker) and often special printer housing. Prusa does not

Material	PLA	ABS	ASA	PETG
Printing temperatures (nozzle/bed) /°C	215/60	240/110	260/110	250/90
Printer enclosure	no	recommended	recommended	no
Heat deflection temperature /°C	55	81	86	68
Printing	easy	difficult	difficult	easy
Soluble with	Tetrahydrofuran, Toluene, Chloroform	Acetone	Acetone	Dichloromethane
Post-processing	difficult	easy	easy	difficult
UV and temperature resistance	low	high	high	high
Vendor	Prusament	Fillamentum	Prusament	Prusament
Price per kg	24.99€	24.00€*	35.28€	29.99€

TABLE 2.2: Comparison of tested 3D-printing materials: PLA (Polylactic acid), ABS (Acrylonitrile Butadiene Styrene), ASA (Acrylic Styrene Acrylonitrile), PETG (Polyethylene Terephthalate modified with Glycol) [62]. *Additional production costs not included.

recommend using their printers for ABS without an enclosure, therefore this option was not tested.

From personal experience and vendor’s recommendation, PLA is the material that is the easiest to print, even for beginners [63]. It is also relatively cheap, which renders it ideal for rapid prototyping. We therefore recommend PLA as the material of choice for the parts of the UC2 toolbox. Due to being made from a bio-degradable material, PLA slowly degrades. This can take years in standard room temperature and other condition but is accelerated by heat or humidity and the object might become brittle. This is not an issue in tinkering and prototyping but if a user wants the parts to last, it is advisable to use a different material.

In several scientific application we encountered a severe issue with PLA, due to its low temperature resistance. This is described by the Heat deflection temperature in Table 2.2, which is in material testing defined as the point at which the test object bends under 0.45 MPa load [62]. We observed significant bending of the baseplates and Z-stages under their own weight in the case of the Incubator-enclosed Microscope [1]. For this application, it is advisable to use the Acrylonitrile-based materials instead.

The 3D-printed parts have a limited life span. Especially inserts with moving mechanism are prone to breaking or the mechanism simply wears of. Around the screws that are used, for example in the connection of a cube body and cube lid, the material is more likely to break, making it in this case impossible to exchange insert in a cube multiple times. Therefore, when a school or a research institution wants to implement the 3D-printed toolbox, they need to consider not only the time and material for the initial production but also for maintenance. Furthermore, a certain level of expertise is necessary for troubleshooting. For this reason, the 3D-printed systems are often inconvenient for them.

A topic that is often not tackled when it comes to 3D-printing is tolerancing. In principle, the reproducibility is high when everyone with a 3D-printer can print the same file. But in practice, the results depend on the 3D-printer model, the material, the exact copy of a printer, the exact spool of filament, room temperature, and other factors, and this can cause a variation of up to 0,5 mm in size compared to the dimension in the design (from our experience). Therefore, it is more useful to provide guidance to the users on overcoming the potential issues, rather than defining tolerances in the classical sense. For the users that are not professional engineers, hence almost all of them, introducing the topic of tolerancing would build an additional entry barrier and it is better to provide tips on solving the resulting issues.

To increase the reproducibility, stability and enable scaling, other production methods were considered and the selected ones are described in the following sections.

2.2.3 Injection moulding

Challenge: Production costs and efficiency, compatibility of IM and 3DP modules

Solution: Design adaptation of cubes and baseplates for IM production, 3DP cube v3 as an open-source equivalent, calibration for baseplate v3 (see section 3.3.2)

Injection moulding is a manufacturing process for producing parts by injecting molten material into a mould [64]. It is the most common method of manufacturing plastic parts. It is a fast and cost efficient method for production of large volumes of the same object.

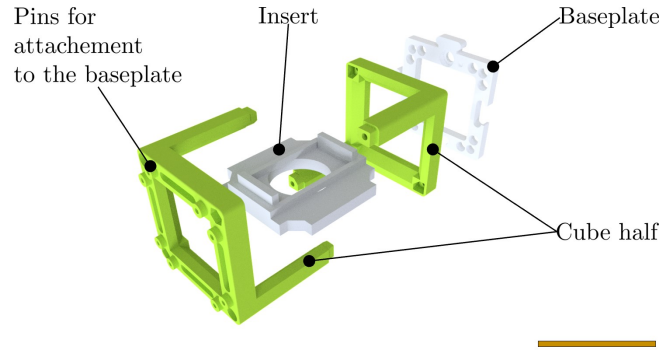


FIGURE 2.1: Scheme of the injection-moulded cube assembly principle.
Scale bar: 50 mm.

As the need for scaling increased, we started to consider other production methods than 3D-printing and we found a collaborator who could support us on going into injection moulding. In the context of the UC2 toolbox, this fits in as a production method of the basic cube and baseplate. These are universal across all modules and applications and thus used in large quantities. Furthermore the printing time of a single cube is very long (around 3 hours), which causes high time demands of the production of any module by 3D-printing. The step into mass production was initially motivated by an opportunity to implement a UC2-based scientific workshop with 150 students. The funding was granted by the Wilhelm und Else Heraeus-Stiftung and the solution to produce enough cubes had to be found in a relatively short time frame.

The design of the cube had to be adapted to the change in production method. The IM cube, shown in Fig. 2.1, was designed in collaboration with the company CNC Speedform AG, Werther, Germany. It is produced using a 250kN injection moulding machine (BOY, 22A, Germany) with ABS as the base material [2]. For each injection moulded part an aluminium form has to be manufactured and the cost of every single form was 10,000 €. Therefore, to lower the development and manufacturing expenses, it was necessary to reduce the amount of different components.

The 3D-printed cube was composed of a cube body and a cube lid, as described in section 1.2.3. The 3D-printed baseplate was always assembled in the CAD software from baseplate units into a size required for a given application, therefore there were many different types of baseplates. There were further requirements of the design, due to the restriction in milling the aluminium form. There must not be any holes from the sides and all holes must be straight, without a more complex profile. As an improvement, it was possible to omit the connection elements and to assemble the IM parts

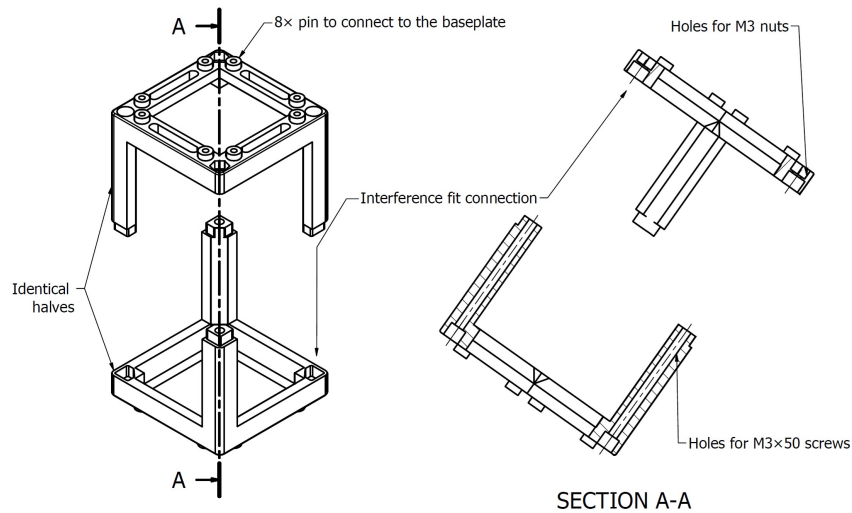


FIGURE 2.2: Scheme of the injection-moulded cube highlighting the assembly and connection features.

by interference fit (press fit), because the production method yields higher repeatability and precision, compared to 3D-printed parts.

The concept of the two-part cube was to be kept but the cube had to be transformed from an assembly of two different parts into an assembly of symmetrical halves, in order to reduce the number of forms needed. Since magnets were not considered safe for the educational applications, it was recommended to find a different way to attach the cube to the baseplate. Due to the increased precision and different possibilities of the production, we switched to a Lego®-like connection mechanism, with pins on one surface fitting into holes in another one. The IM cube (Fig. 2.2) has eight pins on each top and bottom face that fit into the matching holes in the baseplate. Without magnets and using the precise IM parts, screws were no longer necessary to assemble the cube. The cube halves are simply assembled by interference fit. However, we still kept the possibility to lock the module assembly and the cube can be fixed using four M3×50 screws with nuts. The holes for those are marked in Fig. 2.2. The additional holes on the sides of the cube, present in the 3D-printable design in technical drawings in appendix A (DWG02 and DWG03) had to be omitted from the IM cube. They were intended for M3×5 headless screws that would enable connecting any side of the cube to the baseplate, not only top and bottom, but they were rarely used.

The design transfer was carried out by the company on a collaboration base and the time and budget were limited. For these reasons, the possibilities of the design and production were also restricted. One could have considered a cube without a baseplate, for example like in the rendering in Fig. 2.3a, but the methods to produce more complex molds were not available. This would

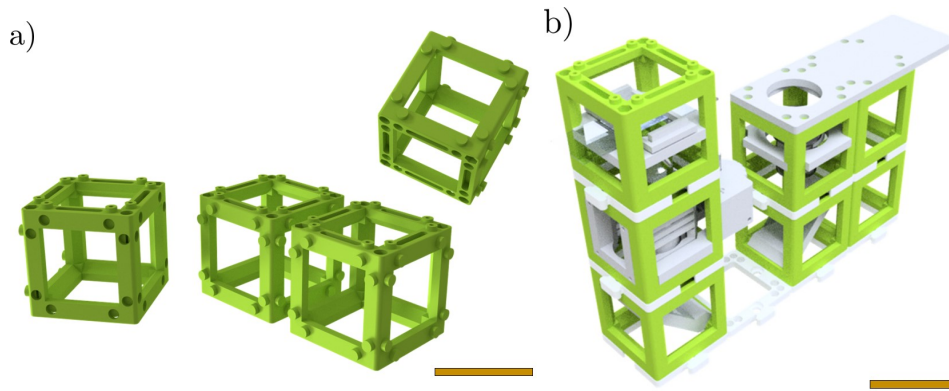


FIGURE 2.3: a) Theoretical model of cubes connected without baseplates, avoiding the offset these create between the layers of a three-dimensional setup. b) Three-dimensional setup with baseplates, the mechanical Smartphone Microscope. Scale bar: 50mm.

have the advantage that no baseplate is needed, hence limiting the amount of moulds and parts. Also in the case of a three-dimensional setup the baseplates add additional 5 mm between the layers (Fig. 2.3b), violating the 4F concept. The advantage of keeping a baseplate was that the setup designs were not affected by the exchange of the production method. In several application, with the Keplerian telescope being a good example, the assembly would require empty cubes to connect the modules, potentially increasing the price. Additionally, it would be more complicated to combine the system with the 3D-printed modules because they cannot be printed with such precise pins and holes. The baseplates also allow easy mounting of the system to an optical breadboard. The need for a baseplate was already introduced in section 1.2.3.

To maintain the open-source nature of the project, the IM cube has to be compatible with a 3D-printable one. Some of the features could be left out of the IM design completely but they were kept for this purpose. One of them is leaving the option open to connect the cube to the baseplate via screws and magnets. The 3D-printed cube cannot be reliably so precise to work on the interference fit principle and it is not possible to print the cube body with the pins on its bottom side. Therefore, for the printed cube it is still the best option to connect a cube lid and a cube body using screws. My contribution was the creation of the compatible cube v3, documented in detail in appendix A, and the version upgrade of the inserts and the GitHub repository. For deeper understanding of the designs, compare Fig. 2.2 and Fig. 2.4 to the technical drawings in appendix A.

The 3D-printed cube can benefit from the increased stability of the IM design when additional $M5 \times 8$ screws are used. We implemented holes in the

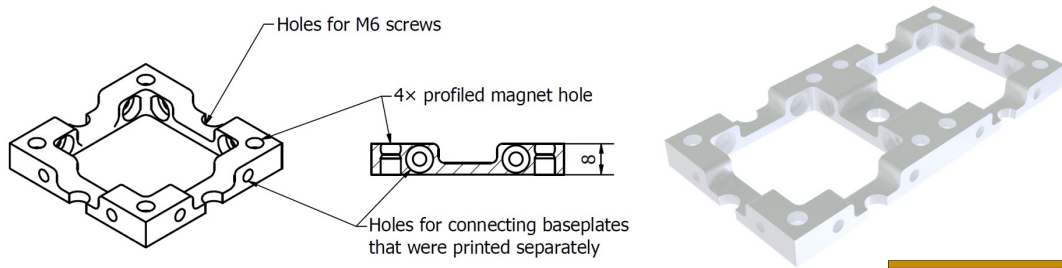


FIGURE 2.4: Scheme of the baseplate version v0 - v2 highlighting the assembly and connection features. Scale bar: 50 mm.

design of the 3DP cube v3, see DWG02 and DWG03 in appendix A, in place of the pins of the IM cube. The M5 screws inserted in these holes work similarly to the pins and provide a more stable connection between the cube and the baseplate. From experience, it is enough to use three M5 screw per cube side (as shown in DWG01).

The IM baseplate unit was transformed into a puzzle piece (DWG04 in appendix A), such that only one form is needed but infinite sizes and shapes of baseplates are possible. The puzzles fit precisely making the baseplate assembly stable using the IM parts. Eight holes are distributed on each side of the baseplate puzzle, to connect to the pins of the cube. The holes for the magnets are included for compatibility purposes described above, but their profile is simplified compared to the cross sections in Fig. 2.4. The baseplate thickness decreased from 8 mm to 5 mm, which is the diameter of the magnets. This way, the baseplate is symmetrical in the IM and in the 3D-printed version, which enables building three-dimensional setups easily (the Smartphone Microscope as an example in Fig. 2.3b). The printed baseplate v2 has holes between the units for M6 screws, allowing the setup to be fixed to an optical table. In the case of the IM design, there are two holes for M5 screws on each puzzle piece to attach to a supporting board. Because the baseplate is thinner, it can also snap to the optical table via the ball magnets.

The IM baseplate puzzle is almost directly 3D-printable. The only design difference is that the holes for the pins go all the way through the baseplate in the printable design. The actual size of the puzzle connections may vary between different printers, the way we overcame this issue is explained in section 3.3.2.

With further scaling of the project, the production of the inserts by injection moulding could be considered. However, due to the price of the aluminium moulds, it only becomes efficient when thousands of copies of the same part are produced.

2.2.4 Laser cutting

Challenge: Design adaptation of the inserts, costs and efficiency

Solution: Alternative inserts designs for production using a laser cutter.
See section 3.2

Laser cutting is a technology that uses a laser to vaporize materials to cut an edge or engrave a pattern. It is precise and very fast, due to which it is optimal for producing a large number of flat parts.

Moving towards even more scalable designs was again motivated by an opportunity to implement a large number of the educational kits and the inability to cover this demand using 3D-printing. We used the Epilog Helix Laser Machine, available at the Lichtwerkstatt Jena maker space, which uses a CO₂ laser and can cut acrylics, plastics, wood, paper, and many other materials, but not metals.

The materials chosen for the inserts are acrylic glass and polyurethane (PU) foam. Both are common materials in laser cutting, easy to process and easy to work with. They can be cleaned with dish soap or in a dishwasher.

The displayed inserts (Fig. 2.5) for the MiniBOX (section 4.1.2) were ideal for this production method as most of them were already designed as a flat component with simple grooves and protrusions to hold the external parts (lenses, mirror). However, the designs still had to be optimized. The details of these optimizations are shown in section 3.2. Laser cutting decreased the production time of the given set of inserts from 12 hours of 3D-printing to 15 – 30 minutes.

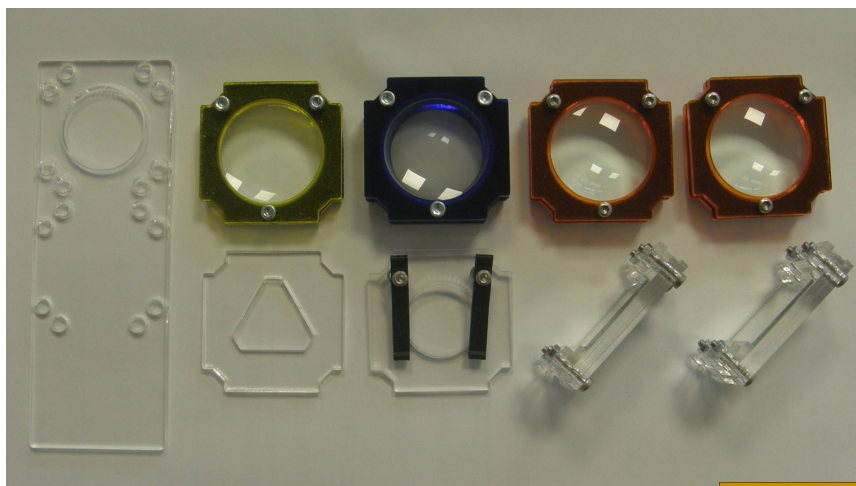


FIGURE 2.5: The MiniBOX inserts selected to be produced using the laser cutter. Scale bar: 50 mm.

2.3 Documentation and community

As discussed in chapter 1, building a community is essential for any open-source project, especially an interdisciplinary one, where the aim is to bridge the fields of physics, engineering, biology, education, and potentially others. Many ideas and improvements of the designs came from the feedback of our users and collaborators and from participants of our workshops. Forming a community is closely related to the documentation, since this is what makes the project truly accessible. Lowered entry barrier invites users and contributors to further improve the system and the documentation, making it even more welcoming for a broader audience.

2.3.1 Open documentation

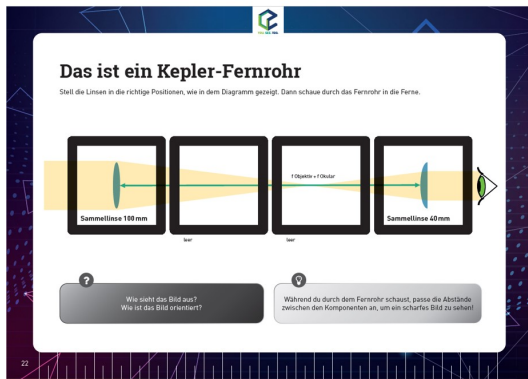

Challenge: Didactics, targeting the users, comprehensive instructions

Solution: Well-structured documentation of the UC2 project, see section 3.5 and supporting educational manuals for the hardware toolbox, see appendix B

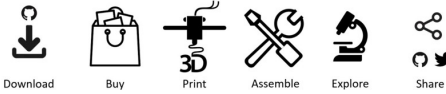

There are two types of documentation, depending on the target group. The end users need to know how to use the system, maybe reproduce it if this is simple enough. This type will be referred to as user manuals (preview in Fig. 2.6a). The tinkerers (potential contributors) need to know how to reproduce and further develop the system, what are the missing but required features and how to include their contribution. This will be referred to as project documentation (preview in Fig. 2.6b). The two groups are not strictly separated and users often become contributors. Active contributors are not easy to find and therefore it is very important to encourage the users to start contributing, even if they start small.

The UC2 project and all its sub-projects are documented in the form of GitHub repositories, all of them available at the openUC2 account. GitHub is an online version-controlled (software) development platform used for storage and collaboration. This allows the more adventurous users to find everything in one place and contributors can suggest improvements to the documentation itself, not only for the hardware and software. The main repository hosts all the basic modules and applications and the entry barrier is kept low there. The open project documentation conclusions are discussed in more detail in section 3.5.

a)

b)  Start here! Everything is open-source - simply join!

Steps to reproduce and use the toolbox:

Too many new things? Follow our tutorials  [From a Beginner to a Professional!](#)

Already familiar? Click here if you are looking for...

TheBOX	General toolbox	Specific setup	Workshops
			
Choose a version and build your own BOX.	Explore the toolbox and its applications.	Alternatives for many Microscopy methods... and more.	Host or join a UC2 workshop.

Get Involved! [Contribute to the project!](#)

... or keep on reading to learn more!

FIGURE 2.6: Examples of UC2 documentation. a) A page from the MiniBOX booklet (appendix B), original size A4. b) A preview of the UC2-GIT main page, showing how to start working with the toolbox.

Audience-targeted hardware development requires user feedback. Especially in the field of education, the school kits could not be improved without testing, and testing was not possible without respective user manuals. Thus we designed the MiniBOX booklet (complete booklet in appendix B). The booklet is discussed in the context of the MiniBOX in section 4.1.2. It is also available on the GitHub repository for improvement suggestions.

2.3.2 Choice of external components

Challenge: Availability, affordability, sustainability

Solution: Adaptable designs, up-to-date open-source documentation

Any hardware project relies on the availability of the components. Since we aim for high accessibility of the UC2 toolbox, we consider the following criteria when choosing external parts:

- **Price:** The components should be affordable in a given category. In case of optical and electronic components, this is related to the required performance of the system.
- **Sustainability:** The parts should come from a reliable vendor that will continue to deliver them in the future.

- **Type of user:** Hackers and makers are looking for a cheap solution and can order from websites such as Amazon, Aliexpress or eBay. Users bound to a university or a research institute have to order from official vendors. It is good to provide an advice on where to buy the parts for both groups.
- **Footprint:** When considering scaling and commercialization, it is our long-term plan to take the CO₂ footprint into account.

It is not entirely possible to guarantee the long-term availability of the external parts, especially for the cheap and off-brand ones. The ability to compensate for such changes is however the advantage of open source. The part list and the designs can be updated by the users when they discover that some external component is no longer available and the complete development history is stored in the GitHub repository. On our side, it is important to provide the specifications that are necessary, for example the wavelength and power for a laser source, and the users can find the alternative available to them.

2.3.3 Practical demands on an open-hardware design

Challenge: Reproducibility by (end) users

Solution: User-oriented design

While working on an open-source project, we learned that not every openly shared design of a part is directly usable by the community. This applies especially when we want to allow the end users to reproduce the system on their own. Our experience is summarized in the following points:

- **A 3D-printable part must print successfully with standard printer settings.** The user cannot be required to dive into advanced settings or alter the *.stl file or the G-code.
- **A part should be rather robust.** Thin elements might not print successfully with a 3D-printer. Small components produced by a 3D-printer or a laser cutter might break during assembly.
- **A 3D-printable part should be printable without support structures.** In case the support structures are necessary, graphic instructions must be provided on how to remove them, especially when a thin part of the component could be mistaken for a support structure.

- **An assembly should consist of the smallest possible number of parts.** This applies to both the number of produced and external components. Assemblies need to be as simple as possible while providing the intended function.
- **Thorough graphical assembly instructions must be provided.** The documentation is crucial for the success of the designed part and the right way of documenting the assembly should be considered early on.
- **A video must be provided for each moving mechanism.** It is important to show the principle and the limits of the movement.

When the above points are fulfilled, the part can be reliably reproduced by any non-professional user, without a need to contact the designer and ask further questions. Nevertheless, it is also part of an open-source project to provide user support and help with troubleshooting, and GitHub offers the “Issue” feature for communicating those with the developers.

2.4 Decision matrix

Challenge: Develop the toolbox for broad audience, both open-source and commercially available

Solution: Commercialization of products developed openly with the community, assign the boundary conditions (section 2.1) to the applications based on their importance

Due to the organic growth of the UC2 project and many opportunities coming from the enthusiasm of the collaborators, we did not base our design decisions on a decision matrix but rather defined a matrix that assigns the criteria to the three chosen applications of the project (see Tab. 2.3). The UC2 toolbox is meant to be used for both education and research, and create a bridge between those two. There is some but not complete overlap of the needs of the users from both fields. In order to bring our system to this broad audience and keep the spirit of the project, we identified several key points important for its future success. The (+) and (-) signs indicate the importance of these key points for a given application.

Tab. 2.3 shows that the demands on the toolbox are very high for it to be applied in all three fields, an open-source platform, education, and open science (microscopy) tool. The solution to this is always considering the target

Toolbox application conditions	Open-source platform	Education kits	Open Microscopy
Easy to operate	++	+++	++
Easy to modify	+++	+	++
Open CAD designs	+++	-	+++
Customization	-	-	+++
Sustainable resources	+++	-	++
Accessible production method	+++	+	+++
Robust designs	++	+++	++
Research-grade performance	-	-	+++
Comprehensive solution	-	+++	+
Creative potential	+++	+++	-
Affordability	++	+++	+
Low maintenance	N/A	+++	+
Project documentation	+++	+	++
User manuals	-	+++	+
Support	+++	+	++
Designed for mass production	-	+++	+
Certified	-	+++	++
Commercially available	-	+++	++

TABLE 2.3: Decision matrix. The (+) and (-) signs indicate the importance of a factor or feature for a given application.

application and using the modularity as a feature that allows reusing the ideas. This feature enables developing the same system for the different applications.

We concluded that to provide an available and accessible system to the users, the next logical step is to found a company or find a producer. However, it is important for us to also keep the project open-source, which is nowadays still uncommon in the commercialization and creates an additional challenge.

Based on the requirements and the available methods (section 2.2), we selected the following production methods for initial scaling-up of the toolbox:

- Injection moulding for the cubes and baseplates - they are universal, repetitive, and used in large amounts.
- Laser cutting for passive inserts - translating the inserts into layered designs where possible.
- 3D-printing for small details and mechanism that could not be transferred into an LC design.
- 3D-printing for a compatible alternative to the mass-produced system and more complex specialized inserts.

Chapter 3

Design optimization

Here, concrete examples of my contributions in terms of designs and toolbox improvements are presented.

3.1 Module examples

Modules are the cornerstones of a modular system. A modular toolbox has the advantage that new ideas can be easily implemented, as long as they are converted into compatible modules. The system is therefore designed in a logical structure, described in our Modular Developer Kit (MDK, available at UC2-GIT) and shown in the scheme in Fig. 3.1. Additionally, more complex large systems can be build compatibly under the condition that they fit the square grid, hence the unit pitch. The currently available UC2 modules are documented in the GitHub repository.

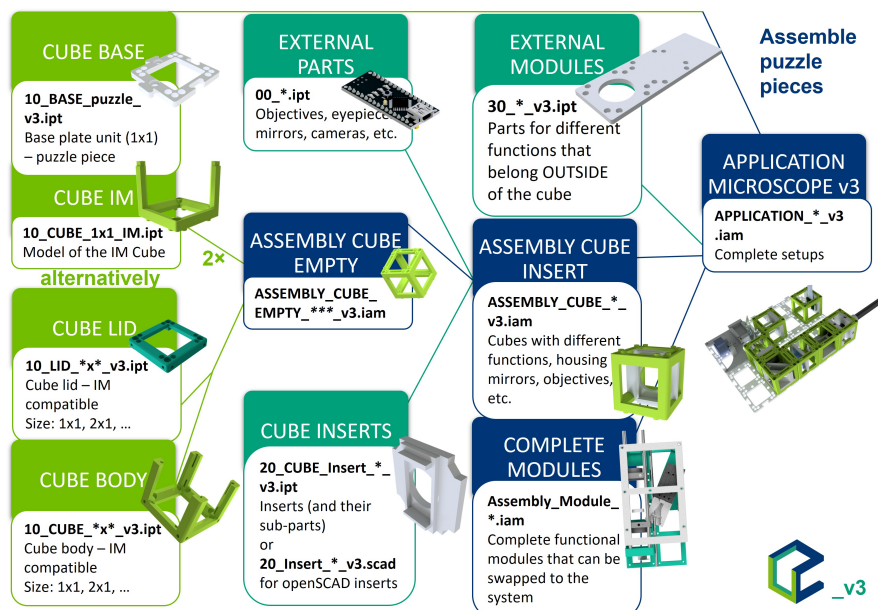


FIGURE 3.1: Modular Developer Kit (MDK), a hierarchy and naming convention of the components (simplified, detailed documentation in [7]).

The criteria defined in chapter 2 set rather narrow limits for the hardware development. The experience of designing or improving a module could be described as “making everything as small as possible and as big as possible at the same time”, because the cube limits the outer size but the mechanisms implemented in the inserts often require extra space. During the development, the criteria were followed with the application and target user group in mind.

In this section, the evolution of several modules with particularly interesting version history or approach is demonstrated, including some of the blind alleys of development. The examples here cover the four most common cases of a UC2 insert development. The lens cube in 3.1.1 is a generic but stable solution for mounting variable external parts. The circular aperture in 3.1.2 shows an implementation of an existing 3D-printable design into the cube. The rectangular aperture in 3.1.3 finds an alternative mechanism when the standard one cannot fit into a module. Finally, the Z-stage in 3.1.4 shows an adaptation of an existing UC2 design for a transfer from the research to the educational branch.

3.1.1 Lens cube

In an optical toolbox, a lens-mounting module is essential. Nevertheless, it was not easy to find a fitting implementation of this and our lens module has one of the most complex version histories, compared to the other modules. It took many iterations to find a stable solution.

Need: Lens mounting module as a key element of the optical toolbox.

Challenge: Exclude commercial mounts, mount lenses with various diameters

Solution: 3D-printed holder, spiral-spring mechanism

Commercially available systems, such as those from Thorlabs, Inc. or Edmund Optics, Inc., offer a simple and reliable solution. Free lenses can be fixed in holders in a threaded hole of the respective size and fixed using retaining rings. The cube v0 was compatible with the one-inch cage system from Thorlabs, Inc. due to the use of the metal rods (details in section 1.2.3), and we used their SM1-Threaded Standard Cage Plates directly in the cubes (Fig. 3.2a).

This increases the price of the module since the price of these cage plates starts around 20€. To become independent of the commercial system and

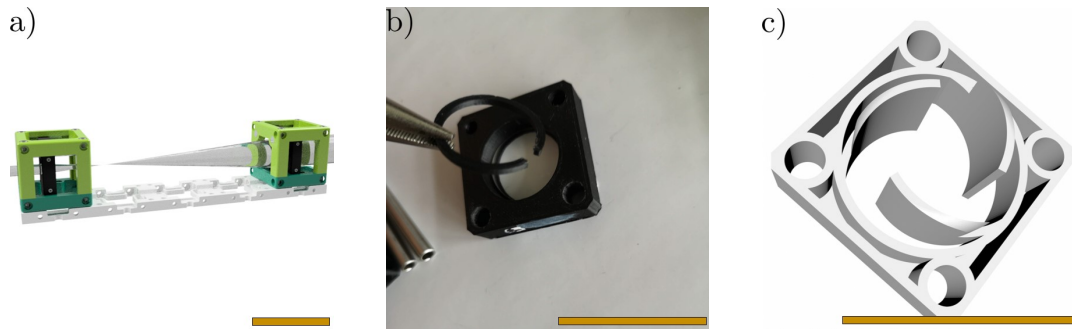


FIGURE 3.2: Early lens holder designs. a) The cage plates mounted in cubes v0, rendering of the Keplerian telescope. b) The 3D-printed cage plated with a C-ring. c) Rendering of the spiral lens holder mountable on the rods of cubes v0. Scale bars: 50 mm.

lower the price (condition from section 2.1), we designed a 3D-printable “cage plate”. Threading is unfortunately not a reliable option in 3D-printing, at least in this size. We designed a rim in the hole of the lens holder and a C-ring (Fig. 3.2b) to fix the lens inside. This mounting principle is often used in telescopes and other tube-shaped optical assemblies. The thin 3D-printed C-ring was not very strong and to fix the lens stably it had to be glued to the holder.

Furthermore, the designed holder had to match the diameter of the lens. In search of frugal solutions, we use a large variety of non-standardized lenses from multiple vendors. The option to have one holder to mount them all was therefore very attractive. The next version (Fig. 3.2c) was based on a flexible mechanism with three arms that were designed to work like springs (inspired by [65]). The advantage of this holder was that it could hold not only free lenses but also mounted lenses or microscope objectives, eyepieces and other components of cylindrical shape, and it was in principle self-centering.

Challenge: Unstable mounting , secure the lens in the holder

Solution: Parametric fixed design

The spiral lens holder went through the upgrade to version v2 (Fig. 3.3a). But with more space in the holder, its issues had a more significant effect. Although the design is in theory automatically centering the lens on the optical axis, in practice this does not always happen. The performance is dependent on the diameter of the lens (how much pressure is applied on the springs), it deteriorates over time, and finally the springs tend to break. It turned out to be especially unsatisfactory for the unmounted lenses, because it was difficult

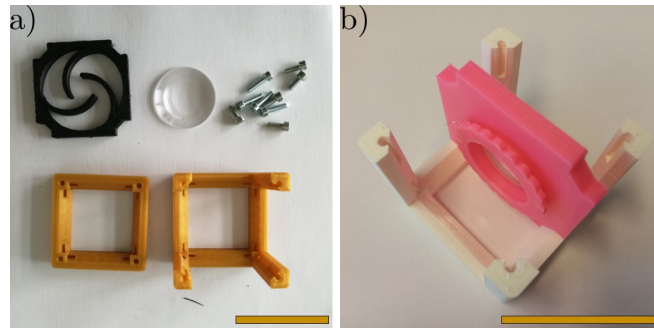


FIGURE 3.3: Lens holder in version v2. a) The spiral lens holder. b) The first parametric holder using an O-ring. Scale bars: 50 mm.

to insert them without touching the optical surfaces and they could easily fall out, which increased the risk of scratching them. This was unacceptable for the educational use of the toolbox (according to section 2.1).

With the rise of the SimpleBOX kit (section 4.1.2) we needed the lenses to be fixed and safe from the fingers of the users. The proposed solution was to design a fixed holder, similar to the standard cage plate, but parametric to fit different lenses. The first parametric lens holder (Fig. 3.3b) was designed in Autodesk Inventor and the original design files were provided with a tutorial to adapt it to a given lens diameter and thickness. The mounting principle was similar to the C-ring but this time we used an O-ring, its outer diameter being $d_{ring} = d_{holder} = d_{lens} + 0.7$ mm, with 0.7 mm being the experimentally found ideal offset for printing. The press fit stability of this connection was dependent on the 3D-printing results and therefore varied among different 3D-printers. Glueing with hot glue was still necessary to ensure safe closing of the insert.

Challenge: Lens size limited, accessibility of the parametric design, fixing the lens inside

Solution: Divide into small and large lens holder, openSCAD design and Thingiverse Customizer (see also section 3.3.1)

Working with parameters in Autodesk Inventor is not very convenient and due to licensing this was not accessible for all users (see section 2.2.1). The openSCAD software is ideal for parametric designs and offers the option of using the Thingiverse Customizer (explained in section 3.3). For the next design (Fig. 3.4a) we therefore switched to openSCAD. This holder was designed with a slightly conic rim on top of the front surface of the insert and a

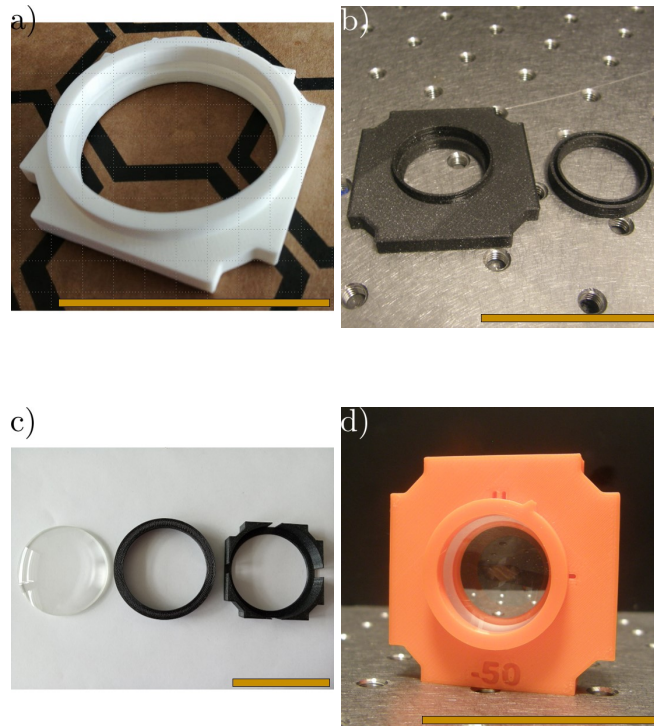


FIGURE 3.4: Parametric lens holder design with openSCAD. a) First version, assembled. b) First version, showing assembly principle. c) The holder for large lenses. d) The latest version of the generic 3D-printed holder. Scale bars: 50 mm.

fixation ring with a groove to fit on this rim (see Fig. 3.4b). This provided a more stable connection, even though not yet ideal.

The parametric design could accommodate lenses up to 42 mm in diameter, due to the presence of the fixation ring. For larger lenses, up to $d = 50$ mm, we designed the holder in Fig. 3.4c. To save space, we returned to the simple O-ring of Fig. 3.3b. However, the design was upgraded in such a way that the hole in the holder and the O-ring were made elliptical instead of round (major axis = $1.03 \times$ minor axis). This way, the O-ring could be easily inserted into the holder and fixed tightly when rotated by up to 90° . The holder needs to be relatively thick (10 mm thickness yields stable results), yielding it inefficient for small lenses, due to the long printing times.

The elliptical fixing solution was later implemented also in the insert for smaller lenses. The rim on the holder and the ring with the groove became elliptical and we added additional markings to indicate the open/locked position (Fig. 3.4d). For user's convenience, we also added the option to 3D-print the focal length of the lens in the holder. The *.scad code is shown in appendix C.

For the objective lenses and eyepiece we kept using the spiral holder, until it was finally replaced by specialized designs. The objective received a

triangular holder, continued in the laser cut version and displayed in Fig. 3.14. For the eyepiece mounting, we simply provide a plane insert with a hole, parametric such that it can be adjusted for any eyepiece.

Challenge: Mass production

Solution: Laser cut lens holder, see section 3.2.3

Fig. 3.4d is also the latest and the most successful 3D-printable lens holder design. For scaling purposes, it was replaced by the later described laser cut insert (see section 3.2.3). But the printable parametric holder (section 4.1.3 and appendix C) still offers the flexibility needed for tailoring by the users.

3.1.2 Circular aperture cube

Need: Circular aperture for the CourseBOX (section 4.1.4).

Challenge: Scale the existing mechanism to fit into the cube, assembly stability, material properties (translucent)

Solution: Iterative design, coating option (opaque)

A (circular) aperture is used to control the amount of light coming through it or the angles of the rays. Although we call the module “aperture”, it would be more correct to call it “diaphragm”, because a diaphragm is the mechanical device while an aperture is the opening in this diaphragm. These terms are often mixed. An iris diaphragm is particularly useful in setting up Köhler illumination [66]. These diaphragms are frequently used in photography and therefore they are of interest to a larger community. In online platforms offering free 3D-printable objects, such as Thingiverse [67], one can find a plethora of iris diaphragm designs (usually under the name “mechanical aperture”), often with a mount to fit photographic objectives.

However, all the available designs were too big for the UC2 cube. We used the “Mechanical Aperture” from Thingiverse user Kajashey [68] (Fig. 3.5a), because it was nicely documented, and adapted and down-scaled their mechanism into a cube insert (Fig. 3.5b).

Fig. 3.6 shows the scheme of the diaphragm. There are two insert plates, fixed together using two $M2 \times 12$ screws with nuts, holding the mechanism between them. This way, it is possible to slide the insert within the cube, allowing its precise alignment. The diaphragm is composed of seven “leaves” (or “blades”), *20_Cube_Insert_CirAp_Leaf* in the scheme. On one end of each leaf

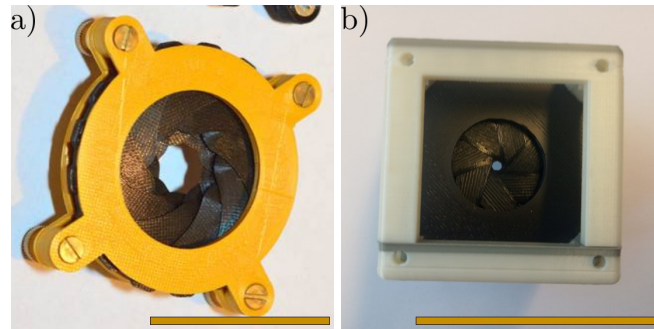


FIGURE 3.5: The circular aperture. a) The original design that inspired the module. b) The mechanism implemented in a cube. Scale bars: 50 mm.

there is a hole that connects the to the *20_Cube_Insert_CirAp_Wheel*. The leaves are regularly distributed around the wheel. On the other end of each blade is a pin. These pins fit in the grooves of the *20_Cube_Insert_CirAp_Guide*, one of the two insert plates. When the wheel is turned, the hole-ends follow it and the pin-ends are forced to slide along the grooves of the guide. Thus, the aperture closes or opens, depending on the wheel rotation direction. The wheel carrying the leaves is forced against the guide by the *20_Cube_Insert_CirAp_Lid_v3*.

The size limit of the cube is a very strict boundary, given that in ideal case the open aperture would not block any light passing through the cube. This is of course not possible and the fully open aperture transmits a beam diameter of 25 mm (Fig. 3.7a). Fully closed aperture still transmits some light through a central area with the diameter of 2 mm (Fig. 3.7b). Since we only used the aperture in the educational applications so far, this has not been an issue because the effect of opening and closing the diaphragm can be demonstrated and complete obstruction of light is not necessary. The opening can be smaller with thinner leaves but that increases the issue of being translucent described

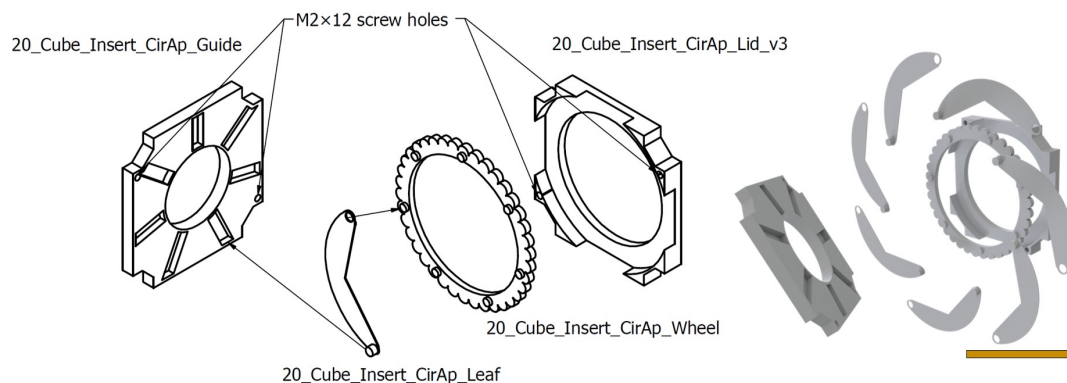


FIGURE 3.6: Scheme of the circular aperture assembly. Scale bar: 50 mm.

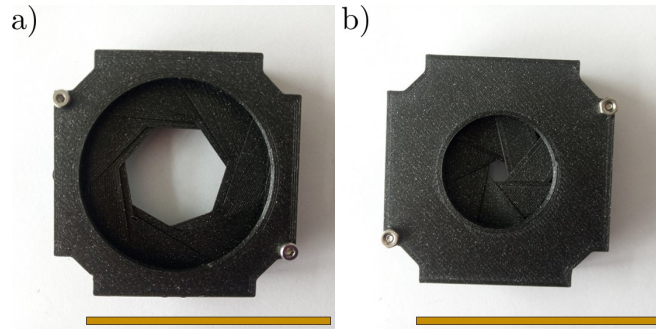


FIGURE 3.7: Opening of the circular aperture. a) Maximum, 25 mm. b) Minimum, 2 mm. Scale bars: 50 mm.

below. We optimized the dimensions to find the ideal balance between these two issues.

A problem arises from the 3D-printing material properties. The leaves are only 0.3 mm thick and even when printed in black material and with the lowest possible layer height, they can be still partially translucent, especially for a strong light source. This has not been so crucial in our setups, as we used the aperture with expanded beam or ordinary flashlight as a light source. To overcome this, the leaves could be painted or covered with a black foil. Then they are fully opaque.

There is another potential issue arising from the tolerancing problem described in section 2.2.2. Although we successfully build several copies of the aperture, it was very difficult to assemble the mechanism when the shrinking of the material was high, because this led to the leaves fitting too loosely on the wheel. We proposed to solve this by making the pins mushroom-shaped but more likely a more complex design update will follow, optimizing the diaphragm for mass production.

3.1.3 Rectangular aperture cube

Need: Rectangular aperture for the CourseBOX (section 4.1.4).

Challenge: Find a suitable mechanism to provide the required function in this size

Solution: Folding doors mechanism implemented

A rectangular aperture offers more variability in blocking the light, compared to the iris diaphragm. The beam path can be partially or fully obstructed in the X- and Y-direction independently, and without symmetry.

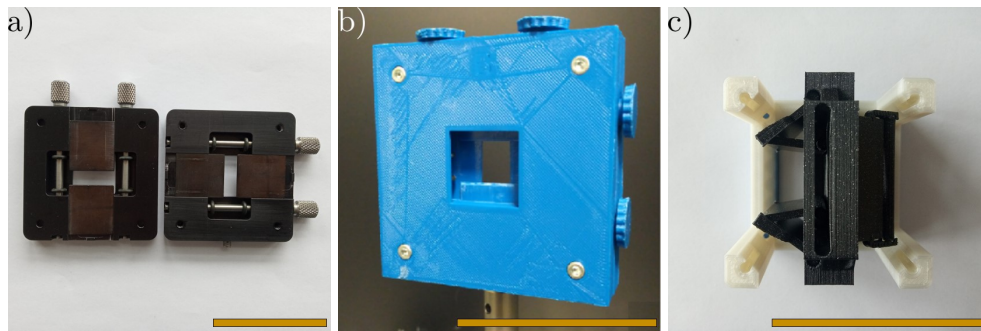


FIGURE 3.8: Rectangular apertures. a) Rectangular aperture (metal), opened to show the principle. b) A 3D-printed version of the standard mechanism. c) An aperture mechanism implemented in the UC2 cube. Scale bars: 50 mm.

Previously (before the modular toolbox), the implementation of the standard design of such a mechanism (Fig. 3.8a) in a 3D-printed form was tested (Fig. 3.8b). In commercially available apertures, there are four blades that can slide in and out. Each blade is controlled via a screw with a rubber O-ring, which presses against the blade. This works precisely and reliably, also in the 3D-printed version. But this mechanism occupies a lot of additional space. In order to have an opening of $20 \times 20 \text{ mm}^2$ the design is already too big for the UC2 cube.

Therefore, we had to come up with a novel design. The idea was to implement a principle similar to folding stacking doors. Initially we considered to print each door (two for X- and two for Y-direction) in one piece as a two-part folding door with a hinge (Fig. 3.9). This would have been very convenient for assembly, but it turned out to be a complication in 3D-printing. Because of the hinge, the doors had to be printed standing and due to their small size and thin design, the print would often fail. This was considered unacceptable due to the criteria defined in section 2.3.3 (a part should be robust). Even though it meant increasing the amount of parts, we decided to split each door into two parts, resulting in eight door components per module. Then they

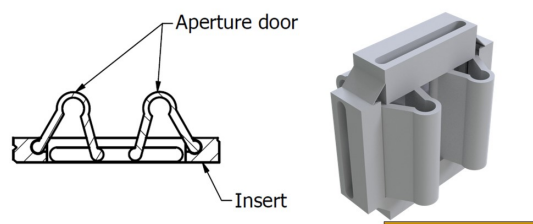


FIGURE 3.9: An alternative design considered for the aperture. Scale bar: 50 mm.

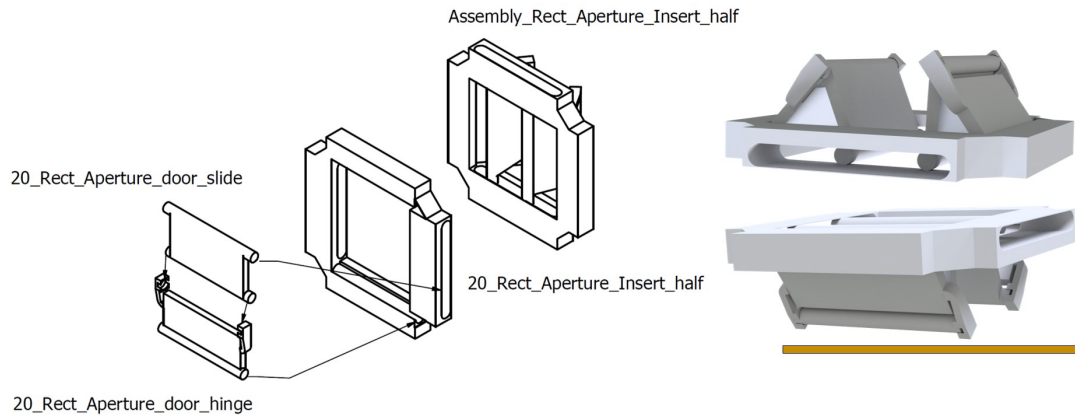


FIGURE 3.10: Scheme of the rectangular aperture assembly. Scale bar: 50 mm.

could be printed flat, which is more reliable, and additionally the door is less translucent (an issue described in the previous section).

The final design of the rectangular aperture is in Fig. 3.8c and a detailed scheme in Fig. 3.10. The mechanism is the same for the X- and Y- direction, only with a respective angle of 90° . Therefore, an assembly of two equal parts is formed. The insert is then printed as a single component, composed of two of the *20_Rect_Aperture_Insert_half*. Each door is made of two parts connected by a hinge (see Fig. 3.10). The *20_Rect_Aperture_door_hinge* is assembled into the insert via another hinge mechanism (cylindrical edge and slit). The *20_Rect_Aperture_door_slide* has pins that lock its edge to the insert slit. The edge then slides along the insert as the door is being closed or opened. To operate the door, we suggest using a 1.5 mm hex key (or for example a hair pin in a more DIY approach). This design was successfully implemented, together with the Circular Aperture in the CourseBOX, see section 4.1.4.

3.1.4 Mechanical Z-Stage

Need: Mechanical-only focusing mechanism for the SimpleBOX (section 4.1.2).

Challenge: Transfer from electronic to a mechanical-only design, from a 2×1 to a 1×1 module, user fear of using the mechanism

Solution: See Fig. 3.13 for early 3DP solution and section 3.2.1 for a solution targeted at lower-level education

A reliable focusing mechanism is extremely important in any kind of microscope. Inspired by the openflexure microscope [32], we decided to rely on a flexure bearing mechanism, a type of a parallelogram. The so-called

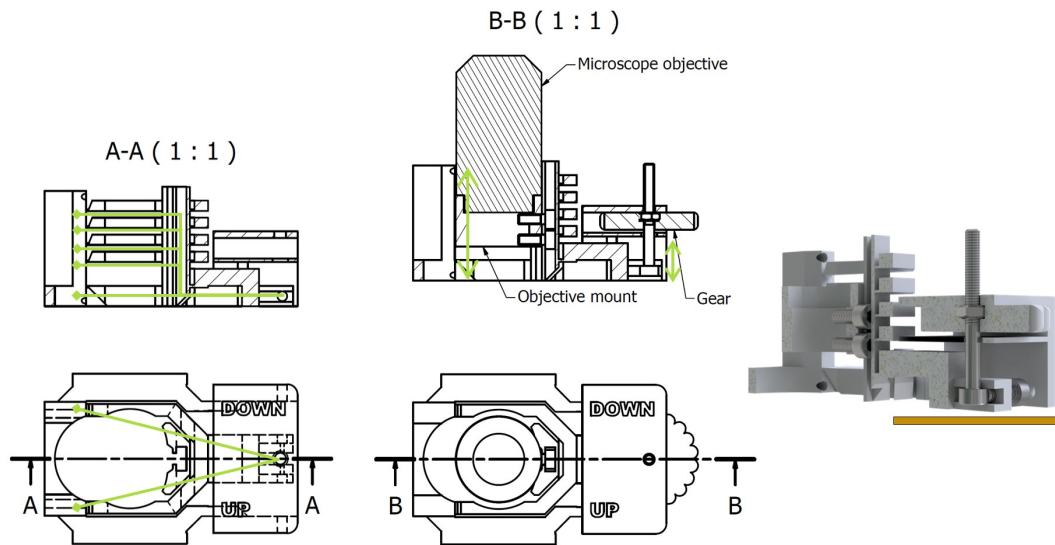


FIGURE 3.11: Scheme of the mechanical Z-stage principle. A-A: The green lines shown the arm of movement. B-B: The green arrows show the directions or movement. Scale bar: 50 mm.

Z-stage was present from the earliest versions of the microscopes, described in section 1.2.3. The movement was powered via a stepper motor (5V, 28BYJ-48 ULN2003), driven firstly by an Arduino Nano board and later by ESP32.

The electronics control poses a greater challenge than the mechanical design and the need for software yields the implementation of this less straightforward. Furthermore, in the educational context, any electronics increases the entry barrier, making the users afraid that they could break something. There are also more aspects to consider in troubleshooting of the software. Not everyone is able to reproduce those modules, due to the lack of tools and knowledge needed for using the electronics. Even though electronic control of the microscopes is definitely something we need to provide, we also had to design a mechanical-only version.

The stage that was the base for this module works on a very basic principle. The mechanism is only a lever fixed to the M3×25 screw head, pushed up and down by (the motor or) the rotation of the gear holding the M3 nut. See the scheme of this mechanism in Fig. 3.11. It also offers two levels of focusing: coarse and fine. Sliding the objective mount, in which the objective is fixed, within the insert provides coarse alignment (30 mm range, long green arrow). The lever mechanism provides fine alignment but only over a short range (5 mm, short green arrow).

Fig. 3.12 shows the first published version of this module. The original Z-stage was housed in a 2 × 1 cube and the motorized stage was directly

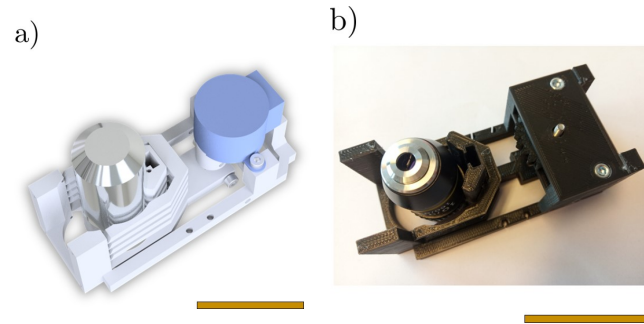


FIGURE 3.12: The early implementation of the (mechanical) Z-stage mechanism. a) Rendering of the 2×1 motorized Z-stage. b) The first mechanical only Z-stage using a gear instead of a motor. Scale bars: 50 mm.

adapted. Instead of using a motor (Fig. 3.12a), a gear was employed to move the lever.

The advantage of this solution was its similarity to the motorized stage. Most of the insert was the same, only a few fast-printing components were added. But handling was very inconvenient, due to the gear being accessible only from the inside of the module, from the space between the objective and the plates that held the gear in position.

When the IM cube was introduced, the use of a 2×1 module was no longer desired. This forced the re-design of the module, the result is in Fig. 3.13. As the insert was adapted for the standard cube, the mechanism was also improved for better handling. The length of the lever, hence the relative position of the screw and the objective, remained the same and so the mechanism was not affected. But the plates that hold the position of the gear were shifted to adjoin the cube face. It was tested that the insert, although the gear-holding plates have to print in the air and without support (demands in

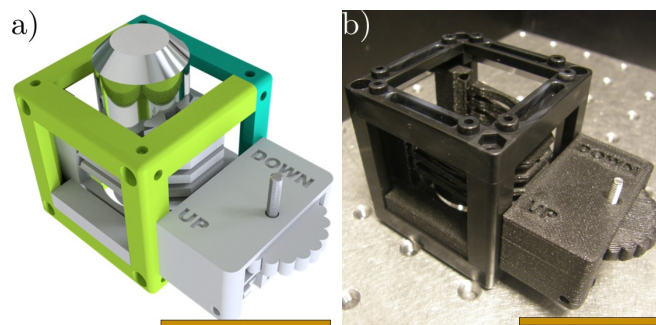


FIGURE 3.13: The 1×1 mechanical Z-stage module. a) Assembly rendering, version v2. b) The Z-stage in the IM cube. Scale bars: 50 mm.

section 2.3.3), can be reliably printed as a single piece, which made it more user-friendly in terms of printing and assembly.

The gear, formerly quite sharp, was re-designed to have round edges for user's convenience. The direction of the movement is indicated by the words "UP" and "DOWN", printed directly in the insert.

For the basic applications in education, we learned that it is better to omit any kind of moving mechanism. However, for many practical applications we are still working on improvements of the 1×1 mechanical Z-stage module, one that is simple and straightforward for the users.

3.2 Laser cut inserts

Need: Fast and scalable insert production for the MiniBOX (section 4.1.2).

Challenge: Design translation from three-dimensional objects into layer-based assemblies

Solution: Tailored for each module (sections 3.2.3 - 3.2.5)

When scaling up the production of the educational kit MiniBOX (section 4.1.2), additionally to the use of the IM cubes and baseplates, we reached for laser cutting as the method of choice for the inserts production, because it is much faster than 3D printing and a laser cutter was available for prototyping in the local maker space.

The original inserts were purely 3D-printed but they were suitable for laser cutting due to them being essentially flat. The design optimizations are shown in detail below. We use the notation 3DP for 3D-printed parts and LC for parts produced using the laser cutter.

The inserts were designed for being made of a 3 mm thick acrylic glass. Additionally, for the lenses, a 10 mm thick polyurethane foam is used as a lining between the acrylic plates. The inserts that are composed of more than one layer are fixed together by stainless steel screws and nuts. The materials were selected to allow cleaning of the modules using ordinary detergents. The lens cube and sample cube were successfully pre-tested on this matter by being left in a dishwasher for more than 10 cycles (auto mode 55 – 65°C, one month in a dishwasher in the institute kitchen, simulating cleaning by the end user in everyday conditions). No changes were observed on the lens holder and sample holder cubes, although temperatures below 45°C would be recommended for PLA.

3.2.1 Objective Holder

Challenge: Create a passive module to lower the user fear

Solution: Single plate insert, interference fit objective mounting

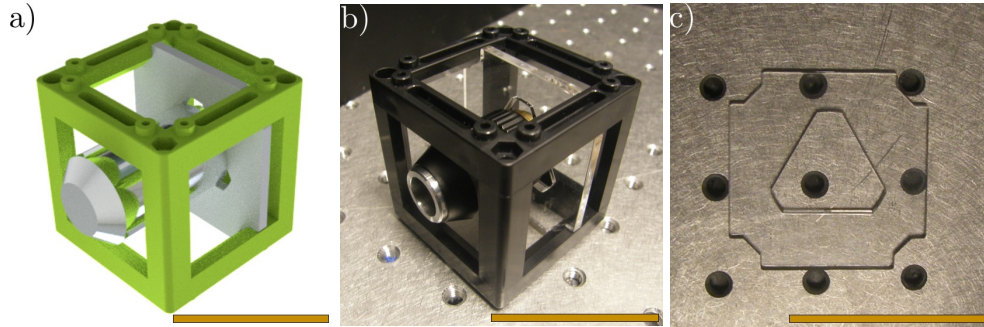


FIGURE 3.14: The objective holder a) Rendering of the IM+3DP model. b) The IM+LC module. c) The objective holder insert. Scale bars: 50 mm.

Originally, the mechanical Z-stage from section 3.1.4 was intended for the MiniBOX but this met with negative feedback, suggesting to lower the entry level even further. Therefore, we mount the objective in a simple insert, the same as was already implemented in a 3DP version (Fig. 3.14a). The objective holder is a single plane part with a triangular hole, in which the objective is pressed into (see Fig. 3.14). The alignment is done by shifting the insert within the cube by hand. It is not intended to remove and insert the objective multiple times but rather insert it once during the initial assembly.

3.2.2 45°-mirror Holder

Challenge: Align and fix the mirror surface on the cube axis

Solution: Layered design creating a symmetrical groove

The purpose of the 45°-mirror holder is to keep a $30 \times 30 \text{ mm}^2$ mosaic mirror in a 45° angle with respect to the optical axes and the sides of the cube and also keep the surface of the mirror in plane with the parallel cube axis. In the 3DP holder, this is reached by the profile of the insert, see Fig. 3.15a.

To achieve the same effect, the LC mirror holder is composed of four plane layers, as shown in the renderings in Fig. 3.15b and Fig. 3.15c. This creates a groove that fits the mirror holder to the edges of the cube. Therefore, the biggest plate goes in the back, followed by the smaller plate on which the

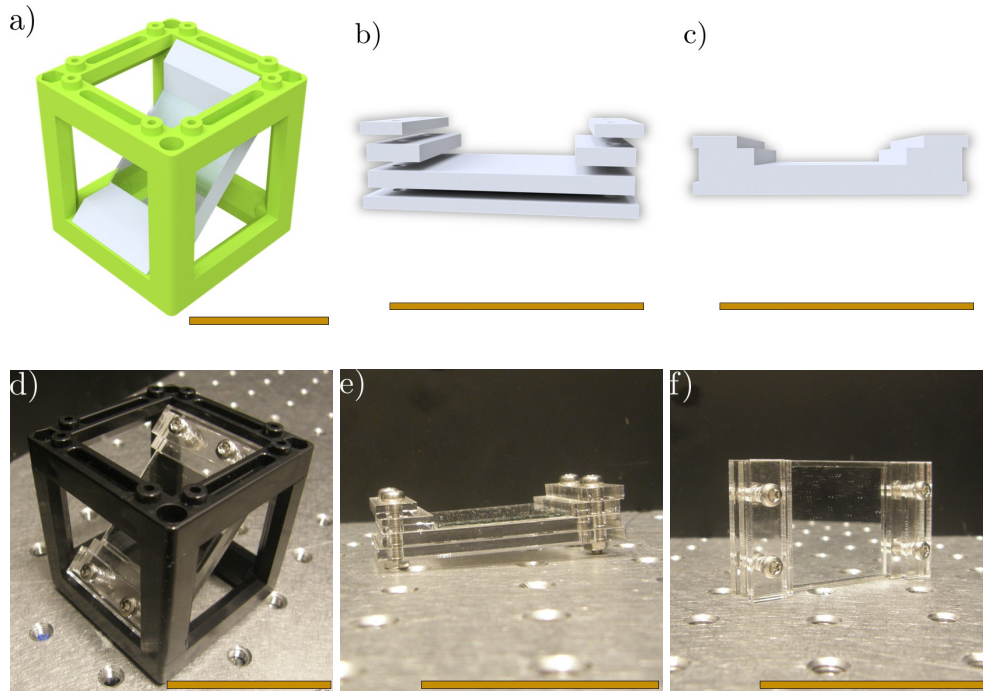


FIGURE 3.15: The 45°-mirror holder. a) The four-layers insert assembly. b) The insert forming grooves to fit the cube edges. c) The assembled laser cut insert. d) Rendering of the IM+3DP model. e) The IM+LC module. f) The 45°-mirror holder insert. Scale bars: 50 mm.

mirror is glued. The mirror is tightly surrounded by two plates (the bigger pair). The smaller pair is on top and has a little overhang on the outer side.

These four plates are mounted together by two pairs of M3×16 screws with nuts, as shown in Fig. 3.15e and Fig. 3.15f.

3.2.3 Lens Holder

Challenge: Compensate for the lens thickness and diameter variation

Solution: Foam middle layer

As described in the previous section, the generic lens holder had a ring to fix the lens inside. This is not an option for the LC insert, but those can be conveniently composed of three layers. To accommodate various lenses, we use the PU foam for the inner layer. The compressible foam layer brings two great advantages. Firstly, the same insert layer works for lenses with edge thickness in the range of 2 – 10 mm and secondly, it allows larger tolerance of the lens diameter, which turned out to be important for the lenses that we selected for the MiniBOX. Each lens holder is composed of two acrylic

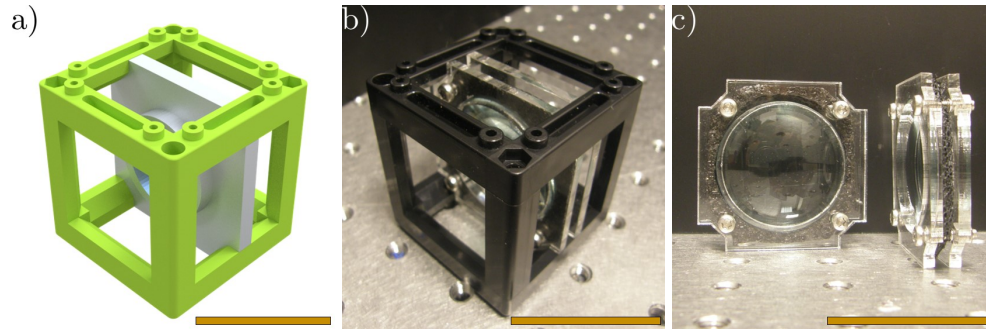


FIGURE 3.16: The lens holder a) Rendering of the IM+3DP model. b) The IM+LC module. c) The lens holder insert. Scale bars: 50 mm.

plates and a foam layer. It is joined together by three M3 screws with nuts (initially four but the amount was optimized). Due to the difference in the edge thickness, we use M3×12 screws for the convex lens with $f = 100$ mm, M3×14 screws for the convex lens with $f = 50$ mm, and M3×18 screws for the concave lens with $f = 50$ mm. The results are shown in Fig. 3.16.

For each lens of the MiniBOX, we use a different colour of the acrylic glass, to distinguish between the focal lengths (see section 4.1.2). The rest of the inserts is made of transparent acrylic glass, to keep the material price low.

3.2.4 Sample Holder

Challenge: Implement a sample clamping mechanism

Solution: Combine laser cutting and 3D-printing

The 3DP sample holder was composed of two printed parts, a holder and a clamp (Fig. 3.17a). The stability varied depending on the 3D-printer and this was not optimal. As the same principle of clamping mechanism was not possible in the LC version, we explored the options and choose a mechanism common in slide holders for microscope stages [69]. These commercially available Microscope Slide Spring Clips are too large for the cubes ($63.7 \times 11.9 \times 12$ mm³ arm size for the cited source, other vendors alike), therefore we had to design our own. We experimented with a fully LC insert but because it did not allow us to implement any curvature in the clamps, we had to go back to 3D-printing.

The sample holder becomes a model example of a combination of “top-down” (laser cutting) and “bottom-up” (3D-printing) production methods, where larger simple fast-produced LC parts are complemented by small

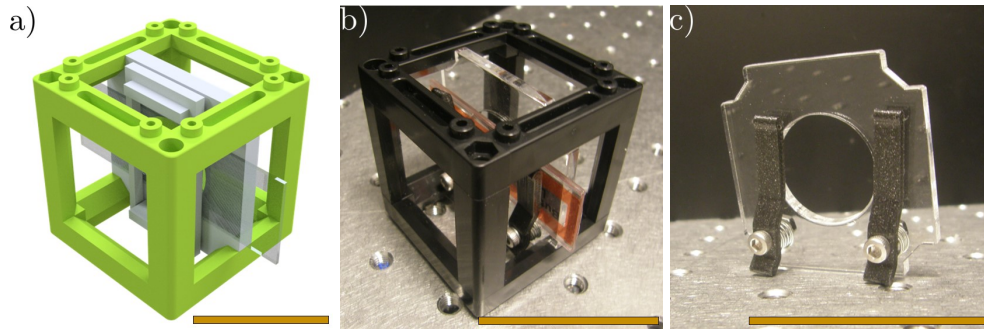


FIGURE 3.17: The sample holder a) Rendering of the IM+3DP model. b) The IM+LC with 3DP clamps module. c) The sample holder insert. Scale bars: 50 mm.

specialized components that benefit from the flexibility of 3D-printing. Two 3DP arms are attached to the insert, holding a microscope slide in position (Fig. 3.17b). The size of one arm is $36 \times 8 \times 6 \text{ mm}^3$. The springs are placed between the arm and the insert and the M3×12 screw is fixed using a nut on the other side of the LC plate.

3.2.5 Smartphone Holder

Challenge: Holder thickness to match the exit pupil plane of the eyepiece and the entrance pupil plane of the camera

Solution: Material thickness, layering

The smartphone holder plate is pressed on top of the cubes. The original 3DP design works directly for the LC part. The only difference is the thickness, which was 5 mm for the 3DP one, but the LC part is again produced using the 3 mm acrylic glass. See Fig. 3.18 for the results.

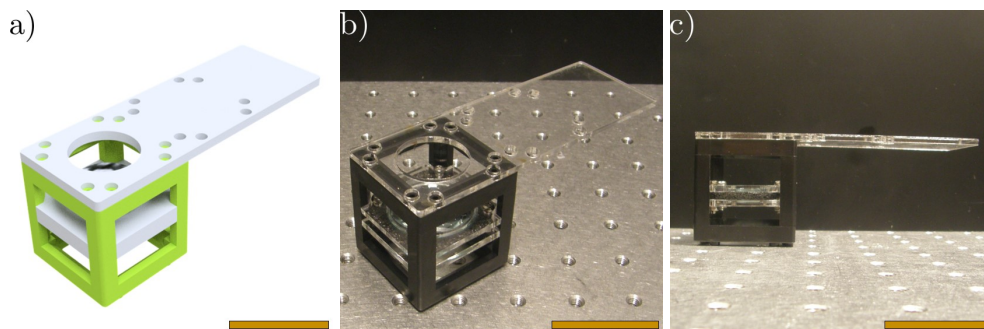


FIGURE 3.18: The smartphone holder a) Rendering of the IM+3DP model. b) The IM+LC module, perspective view. c) The IM+LC module, side view. Scale bars: 50 mm.

The holder thickness needs to be evaluated once more, to ensure the correct distance between the eyepiece and the camera can be achieved. The same design could be also cut from the thicker acrylic plate. Alternatively multiple layers could be stuck together using screws or glue.

3.3 Parametric designs

Need: Accomodation a large variety of lenses and compensation for imprecision of 3D-printing (demands in chapter 2).

Challenge: Adaptable designs

Solution: openSCAD as a design software for parametric components

While some of the modules, for example the 45°-mirror cube, are universal across all the applications, others might need adjustment for each use case. But not all the users are able to adjust the mechanical designs themselves. This is not only due to the use of the proprietary software but also the skill level requirement for altering the original design files.

To offer an easy way of generating tailored *.stl files, we rely on the Customizer App (see Fig. 3.19), MakerBot Industries, LLC, New York City, USA. It is available on their online platform Thingiverse [67]. The app processes a file designed with the openSCAD for parameter customization and allows the user to change the parameters and create the object without understanding the code. The *.scad files are provided in the GitHub repository for advanced adaptations.

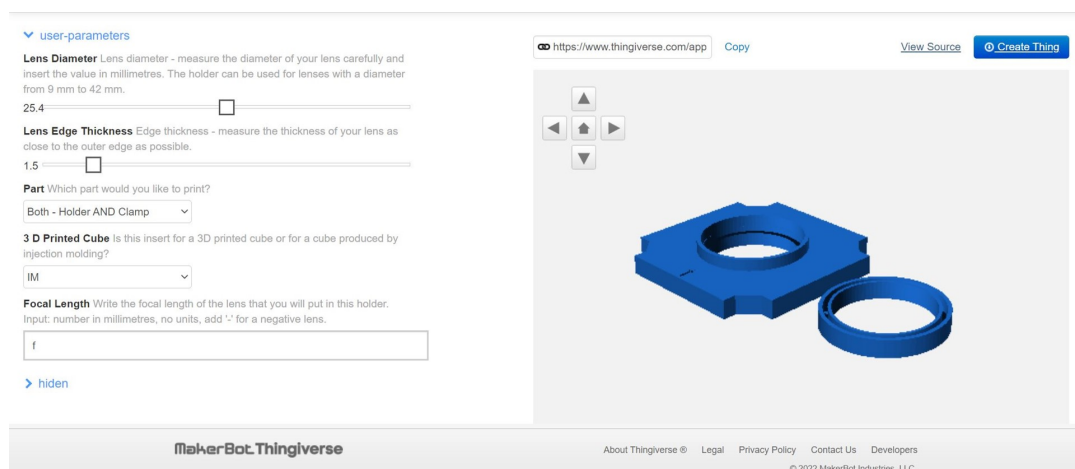


FIGURE 3.19: Preview of the generic lens holder (parametric) edited in the Thingiverse Customizer, openSCAD source code in appendix C.

3.3.1 Generic lens holders

Challenge: Accessibility of the adaptation feature to a broad audience

Solution: Thingiverse Customizer

As already mentioned in section 3.1.1, in order to mount lenses with different diameters and thicknesses, we designed the lens holders that can accommodate almost any object of circular symmetry, such as a lens or a filter (up to two inches in diameter). The lens is fixed inside the holder using an elliptical clamp, as described in section 3.1.1.

The holders are displayed in Fig. 3.20. The one in Fig. 3.20a is able to house lenses with diameter in the range of 9 – 42 mm and edge thickness of 0.5 – 9 mm [70]. The holder for large lenses in Fig. 3.20b is for diameters of 42 – 50 mm and edge thickness of 0.5 – 10 mm [71].

The two parameters, `lens_diameter` and `lens_edge_thickness` can be adjusted using the openSCAD code or Thingiverse Customizer as described above. Additionally, for the holder of smaller lenses, it is possible to input the focal length as a parameter and have it inscribed in the 3D-printed holder.

The openSCAD source code is attached as appendix C. The first part of the code marked as `/* [User Parameters] */` is the part read by the Customizer as editable. The whole design is parametric, the rest of the parameters is marked as `/* [Hidden] */`.

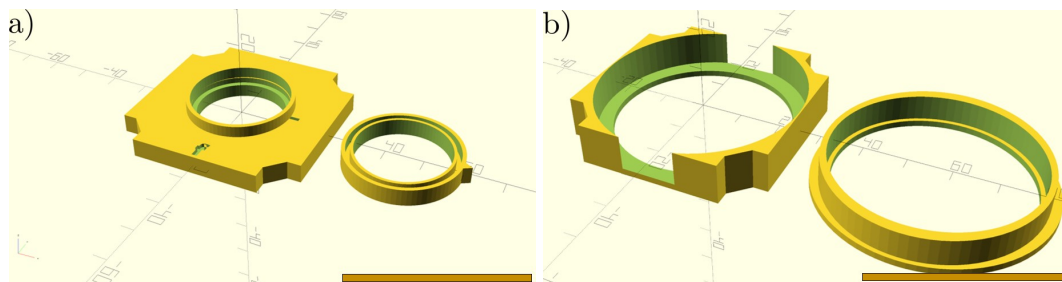


FIGURE 3.20: The openSCAD preview of the parametric lens holders. a) The generic lens holder, lens diameter = 25.4 mm, lens thickness = 1.5 mm. b) The holder for large lenses, lens diameter = 48.55 mm, lens thickness = 2.33 mm. Scale bars: 50 mm.

3.3.2 Calibration of baseplate printing

Challenge: Compatibility of 3DP and IM baseplates, tolerancing of 3DP parts

Solution: Combination of a 3DP calibration tool and a parametric design

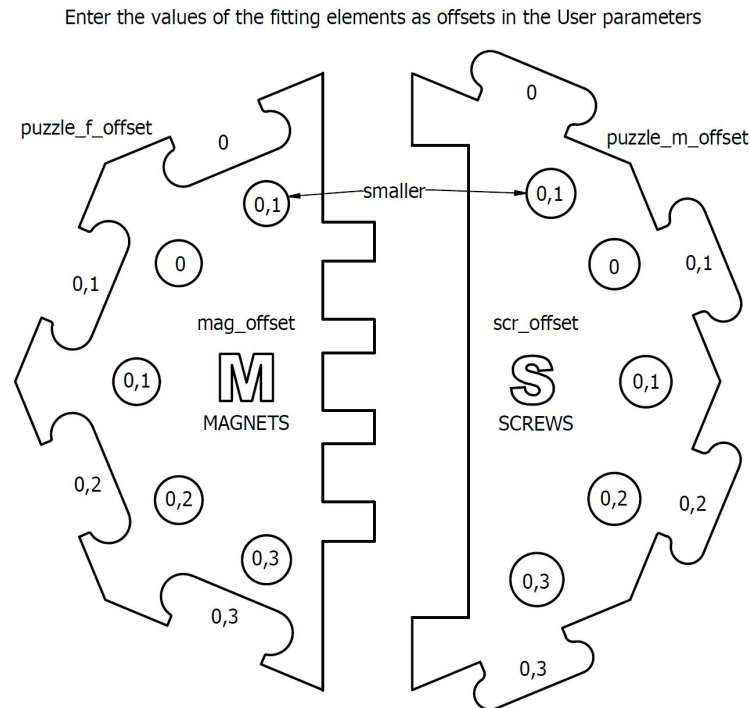


FIGURE 3.21: The user-guiding scheme to select the right offset in the parametric design of the baseplate based on the fit of the printed calibrator.

The 3DP puzzle pieces are never as precise as the IM ones and their actual size varies between different 3D-printers, as discussed in section 2.2.2. This may lead to the 3DP puzzles not fitting together, hence prohibiting the baseplate assembly. To overcome this issue, we designed the calibrator in Fig. 3.21, a tool printed to test the size difference between the design and the printed part for a specific 3D-printer. This comes together with a parametric openSCAD design of the 3D-printable baseplate puzzle (available on GitHub [7] and Thingiverse [72]), where these offsets (the size differences) are included as user parameters and the resulting design compensates for the differences caused by the printer.

There are three aspects that can be adjusted. The *mag_offset* defines the offset for the magnet holes. The *scr_offset* is for adjusting the size of the holes in which the pins of the IM cubes or the M5 screws on the 3DP cubes fit. The last but most important thing is to adjust how the puzzles fit together.

To test that, the calibrator is printed in two parts, one with the male puzzle connectors and the other with the female counterparts. By finding which pair fits the best, the two offsets, *puzzle_f_offset* for female and *puzzle_m_offset* for male are determined.

For printing the baseplate puzzles successfully it is important to avoid a common 3D-printing issue known as the elephant's foot. This means that the first layer of the print is slightly larger than the rest, due to uneven cooling. This can have significant effect on how the puzzle pieces fit together. Fortunately, there is available slicer software that can conveniently compensate for it, such as the PrusaSlicer [73].

3.4 Alternative building block units

Challenge: Mechanically overdefined design of the modules causing stability issues

Solution: Three-point connection cube and hexagonal modules tested, IM cubes as a solution

The design of the 3DP cube is from the beginning mechanically overdefined, due to the connection via four points (magnet to screw), because four points can in practice hardly be in one plane and it is even less probable that the two planes would perfectly match. From the mechanical point of view, a three-point connection should in theory be optimal. We tested some alternative designs, the results are presented in this section, and the details cited here are also documented in the GitHub repository.

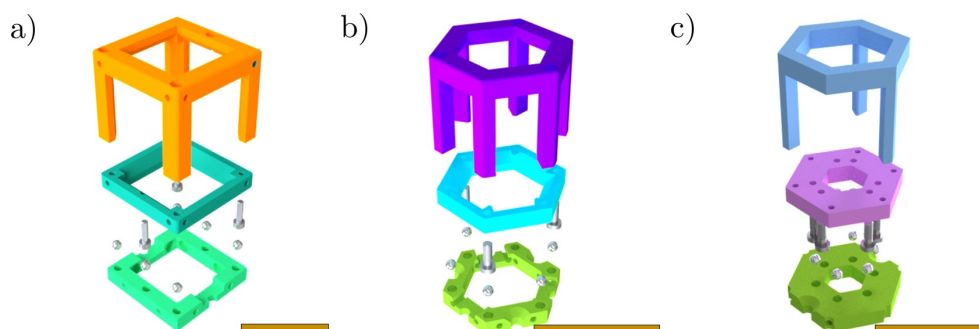


FIGURE 3.22: Alternative modular designs using three connection points between the cube and the baseplate. a) The three-point cube. b) The hexagonal block, version 1. c) The hexagonal block, version 2. Scale bars: 50 mm.

3.4.1 Three-point cube

In this design (Fig. 3.22a), three instead of four screw holes are placed in the cube lid and the bottom of the cube body. Two additional magnet holes are added to the baseplate, to allow the same freedom in connecting the cube and the baseplate. It is convenient that the original inserts are compatible with this design.

Experimentally, this design was impractical for the following reasons:

1. Tipping stability in the unoccupied triangle vertices. In the attachment points, there are no problems but in the screw-free points, the gap between the baseplate magnets and cube influences the stability of the system. Even when low pressure is applied on the screw-free corners, the cube moves.
2. To connect the cube lid and cube body, additional two screws are necessary for proper attachment.
3. Six magnets are used instead of four per baseplate unit.
4. The additional screws and magnets increase the price of the setup.
5. Due to more magnets per unit and hence shorter distance between them, stability problems occur because the cubes are attracted to the neighbouring positions.

3.4.2 Hexagonal building unit

Hexagonal honeycomb structures are inspired by bee honeycombs. These structures are very stable in nature and find many applications in the fields of engineering [74]. Hexagons are also better for three-point connection, as compared to cubes, and offer more angular flexibility. Six magnets are inserted in each baseplate unit and three screws are placed in the corner of an equilateral triangle in the lid and hexagonal body.

There are two different hexagonal designs in Fig. 3.22. The outer dimension (between the opposite edges) is 50 mm, the same as for the cube, such that the baseplate could be mounted on an optical table. Thus, the inner dimensions (distance between neighboring vertices) are smaller than those of the cubes. New set of inserts had to be designed for the hexagonal blocks but issues occurred due to the limited space, as some components, namely of the Thorlabs one inch system, were no longer compatible.

Due to the limited space inside the building block (version 1, Fig. 3.22b) a second version was designed to overcome its issues. In version 2, Fig. 3.22c, also the location of magnets is changed to offer more possibilities for the mutual positions of the hexagons. The block can be turned around with 60° step and moved by half a unit (25 mm).

The problems of the hexagonal building blocks were:

1. In the version 1, several external components (for example flashlight, objectives) could not fit into the hexagonal block and specialized holders, using only the lid, had to be designed for those.
2. Hexagonal blocks could only be used in X,Y -plane and designing a three-dimensional setup would be challenging.
3. The freedom to move an insert in X - and Y -direction inside the block decreased.
4. It is much more difficult for people to think in a hexagonal grid, compared to square grids.
5. Points 3, 4, and 5 of the issues of the three-point cubes also apply here.

It was an interesting conclusion that the theoretically optimal solution is not always the best one when 3D-printing is the production method. 3D-printing always brings a certain disadvantage in stability and performance of the system that cannot be overcome by the theory of mechanical design.

To sum up, we decided to continue working with the four-point cubes, because the theoretically more optimal designs yielded even more disadvantages. In the end, the stability issue was overcome by switching to the IM cubes and baseplates.

3.5 Documentation on the GitHub repository

Need: Lower entrance level and higher educational value of the UC2 toolbox.

Challenge: Didactical structure of the documentation, entry level

Solution: Repository hierarchy, tutorials, feedback loop with the target users

Even though there is not yet one unified definition of how to document a piece of open hardware, it is generally advisable to share and explain as much

as possible. While building it, the user who wants to reproduce it most likely needs additional explanation of the methods used, the working principles, and possibly other background information.

We had the opportunity to improve our project documentation with the help of the Open Hardware Leaders online course [75]. This, together with the inspiration and feedback coming from the Open Microscopy community helped us to establish a high standard of our documentation. Here a few points are named, which are not that commonly found in many GitHub repositories, but we would suggest them for any open hardware documentation.

For an open-hardware project, the assembly instructions are crucial and have to be clear and unambiguous, supported by graphics, and easy to find. When a method is used, it is important to provide means (by additional explanations or external links) to learn the basics for those who are new to it.

3.5.1 Signposts and structure

While a logical structure is usually considered when designing a website, in the case of GitHub repositories, this is rarely the case. But with a hardware project, the repository becomes very large very easily, given that there is not only the hardware design, but also some software, electronics, the assembly and usage instructions. GitHub does not propose any structure and the hardware developers tend to forget that their documentation is not as clear to the users as it is to them. Even a very keen contributor is discouraged if they cannot find the information they are looking for.

In the UC2-GIT we use signpost icons to indicate where to look for information. There is a clear instruction on where to start when reproducing a setup. The many sections are interlinked and the specialized repositories are linked to the main one. We recommend this to any open hardware project documented in GitHub.

If possible, the structure is alike in all parts of the documentation. There is a template of a module page, an application page, and also a repository template for adding a specific UC2-based device. The structure of those pages is very similar, making it easier for the user to navigate through them. All assembly and alignment instructions are aided by many pictures.

To provide an easy access to all the *.stl files, we got our inspiration from the openflexure microscope [76]. Using the UC2-configurator [77] developed together with GitHub contributor “AlecVercruysse”, the user selects single modules or an application and the configurator searches GitHub for the respective files and generates an archive for downloading them.

3.5.2 Tutorials and guidelines

Because our aim is to keep the entry barrier really low, we focus on providing enough guidance for the beginners, the users that are not so sure they can reproduce the system themselves or feel like it would be too much effort to start. Our tutorials section[7] provides information on multiple levels, inspired by [78].

The *First Steps* offer background information on the related topics. Here we rely on external sources but provide an opportunity to learn about 3D-printing, optics, electronics, software, and also contributing to a GitHub repository.

For the *Tutorials*, we designed a path of ten steps, taking the users by hand from printing their first cube to building the educational MiniBOX. The pages of the Tutorials series are typically simpler than the other assembly instructions. A reward-motivation concept is implemented here. When following the tutorials, the modules are build in such an order that for every step or two, a new experiment is realized. This idea proved itself especially useful when we supervised pupils on their high school seminary projects (“Seminarfacharbeit”, see section 4.2.2), who, thanks to the tutorials, needed significantly less help from our side in the initial phase of their work.

After the tutorials, we present a number of *HOW-TO Guides*. These offer solutions to less basic questions or additional information that is useful for some users but not necessary for starting with the toolbox.

Last but not least, the *Reference Guides* provide more information on specific topics and technical details. There is a lot of focus on microscopy-related topics and links to other DIY-microscopy projects.

In addition to the written instruction with images, we prepare explanatory videos. The openUC2 YouTube channel [79] hosts assembly and usage instruction but also demonstrations of experiments and of the possibilities of the toolbox.

Chapter 4

UC2 toolbox in STEAM education

This chapter shows the results achieved in the development of an educational hardware kit and the findings and experience of the development. The educational kits developed over time along the general toolbox and here we present the key events and decisions that defined the current state. Two of the educational microscopes, the Smartphone Microscope and the Light Sheet Microscope are described in detail here.

Need: Comprehensive education kit for different education levels and applications + support creativity of students + ensure validity of results

Solution 1: Define multiple BOXes optimized for each **Target group** (section 4.1)

Solution 2: Creative tasks in the form of project-based education (section 4.2)

Solution 3: User feedback loop for iterative improvements, testing with end users (section 4.3)

4.1 Classroom kits

Before the detailed description of the design decisions that led to the results, it is important to define two terms. The development stage referred to as “prototype” is a version produced with the scalable production methods and ready for mass production. On the other hand a “functional model” provides all the functions but the parts may be produced using rapid prototyping methods, in this case 3D-printing.

The educational kits described in this section developed iteratively, mostly as reactions to the tests with the end users, as discussed in section 4.3.1. The development was often powered and motivated by a specific demand. The resulting sets have an innovative potential but it is up to the market to decide whether they will become a successful innovation.

Experiments	BOX				
	Full	Mini	Simple	Course	Polar
Lens as a Magnifying Glass	x	x	x		
Projector	x	x	x		
Telescopes	x	x	x		
Smartphone Microscope (mechanical)		x	x		
Incubator-enclosed Microscope	x				
Incubator-enclosed Microscope with fluorescence module	x				
Smartphone Microscope (electronic)	x				
In-Line Holographic Microscope	x				
Light Sheet Microscope	x				
Double-Slit Experiment	x				
Michelson Interferometer	*				
Mach-Zehnder Interferometer	*				
Abbe Diffraction Experiment	*			x	
Compound Microscope and Köhler Illumination	x			x	
Polarization Experiments					x

TABLE 4.1: Overview of the experiments covered by each BOX. For those marked with * it is necessary to use two copies of the FullBOX together.

In the perspective of the commercially available educational kits mentioned in section 1.2.4, we can think of the FullBOX as a comprehensive alternative to the Thorlabs Discovery product line, containing similar experiments as their products. The Optical Microscopy Course Educational Kit has its alternative in the CourseBOX and the PolarBOX is comparable to the Polarisation and 3D-Kino Kit. The MiniBOX and SimpleBOX could be an alternative to the building kits from fischertechnik GmbH. In all these applications, the UC2 classroom kits are meant to be easier to use and provide more at lower costs while keeping the creative potential.

The tables here present an overview of the educational BOXes. Tab. 4.1 shows which experiments are covered by which BOX. The polarization experiments are listed separately in section 4.1.3. Tab 4.2 displays the kind and number of modules contained in the BOXes. My original designs are marked as bold, and my most-important modules are described in section 3.1. The complete and up-to-date Bill of Materials of all BOXes, experiments (Applications), and modules is available in the UC2 GitHub repository [7].

Modules	BOX				
	Full	Mini	Simple	Course	Polar
<i>Baseplate puzzle piece</i>	16	8	12	16	16
<i>Circular aperture</i>	1			2	
<i>Rectangular aperture</i>				1	
Beam expander	1			1	1
Beamsplitter	1			1	1
Dichroic beamsplitter	1				
Eyeball				1	
<i>Smartphone holder</i>	1	1	1		
Eyepiece	1		1		
Flashlight	1		1	1	1
LED matrix	1				
LED	1				
Laser	1			1	1
Cylindrical lens	1				1
<i>Objective holder</i>	1	1			
<i>Lens holder</i>	4	4	5	8	6
<i>45° -mirror</i>	2	2	2		1
Kinematic mirror (45°)	1				
Kinematic mirror	1				
Raspberry Pi camera	1			1	
S-stage (Sample)	1				
Sample holder	1	1	1	2	5
Sample holder (comb)	1				
<i>Z-stage (mechanical)</i>			1		1
Z-stage (objective)	1				
Linear polarizer					2
Raspberry Pi with a screen	1			1	

TABLE 4.2: Overview of the modules contained in the BOXes. The modules in bold are my original designs. The modules in italic are described in detail in chapter 3. The modules that were not designed by me and were not particular milestones are not discussed in detail in this thesis but can be found in [7]. Raspberry Pi computer with a screen is not a UC2 module but it is included in the BOXes for hardware control and image acquisition using the UC2-GUI (Fig. 4.2).

4.1.1 FullBOX

Target group: University students, higher level education, demonstration of multiple light microscopy methods

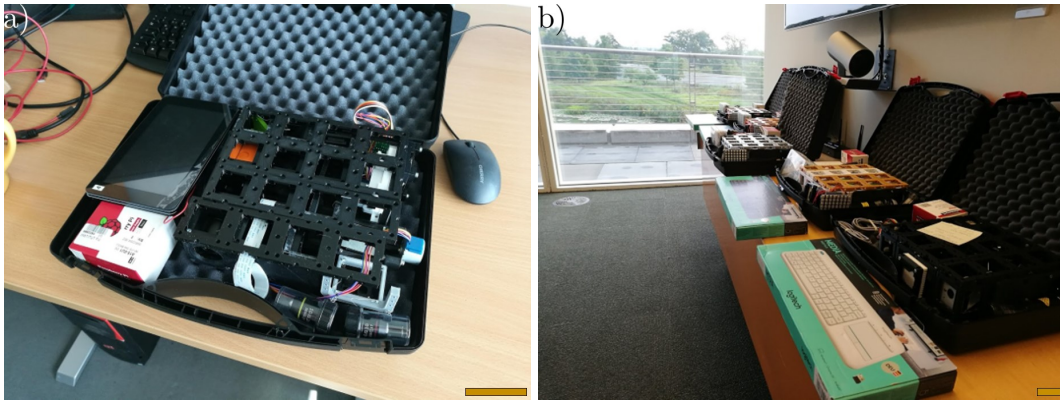


FIGURE 4.1: The first version of the FullBOX. a) TheBOX, covering the available UC2 applications. b) First test of TheBOX (five copies) at the Janelia Research Campus, USA. Scale bars: 50 mm, personal project documentation, B. Diederich.

In the educational context, we received suggestions to compile the toolbox into a comprehensive classroom kit. The concept of *TheBOX*, the idea of such comprehensive kit, was introduced in August 2019, after the Photonik-Akademie Innovation camp held by the Lichtwerkstatt Jena maker space. A group of participants worked for a week on this concept, which boosted the development. Five copies of *TheBOX* (Fig. 4.1) were used in a workshop a month later (see section 4.3.1) and the concept proved to be successful. The issues were mostly with the software and electronics.

One kind of kit could not fit all applications (contain all experiments on different education levels) and therefore the development spread from here. The original compilation was named *FullBOX* and intended as the most complex version, composed of many modules, offering many (at this time all available) applications, and it was equipped with electronics and a Raspberry Pi computer with the UC2 graphical user interface (GUI) installed (Fig. 4.2).

The *FullBOX* was used in workshops (section 4.3.1) later on and it is also subject to the upgrades to v3 and IM cubes. The overview of the included experiments and modules is given in Tab. 4.1 and Tab. 4.2. Note that some of the experiments can only be build using two copies of the *FullBOX*. This assumes the use in a classroom or a workshop, where small groups work with one box each, and two groups join forces to do these advanced experiments. If

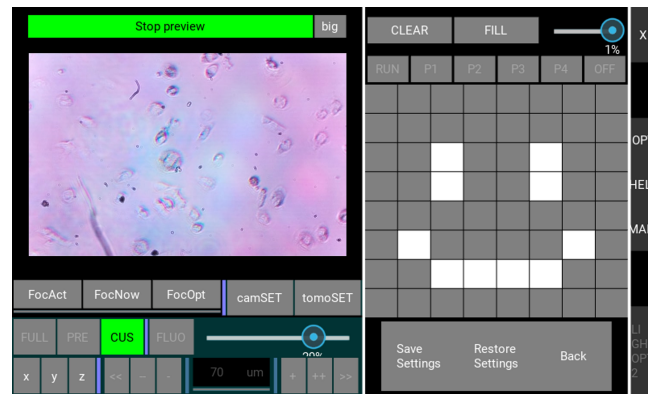


FIGURE 4.2: Preview of the UC2 graphical user interface [80].

someone needs a single box for demonstrations, the FullBOX can be extended with three extra modules (kinematic mirror, beamsplitter, circular aperture), which enable performing those three experiments of the list above. We tested this when providing an extended FullBOX for the Microverse Imaging Center, Jena.

Further note that the Incubator-enclosed Microscope is a simple microscope, which refers to a finite-corrected imaging system with only an objective. A compound microscope is composed of a finite-corrected objective and an eyepiece, like in the case of the Smartphone Microscope. The Incubator-enclosed Microscope offers bright field transmission imaging and quantitative phase imaging, its fluorescence version is an epifluorescent microscope.

The FullBOX is optimized for its application. The events where it was tested are listed in section 4.3.1. However, there are still some serious issues that prohibit development to the state of a prototype. The most limiting is the current state of software and electronics, which is outside the scope of this thesis. Additionally, there are still unresolved problems with the external parts for a comparable open-source version according to the criteria in section 2.3.3.

Some external components are not accessible enough to fulfill the standards of the toolbox (see section 2.3.2). The module hosting the filters is available, but the main restriction is the price of the filters or a limited supply of low-cost ones. Although we had some good experience with lighting filters from the music industry (Lee 010 medium yellow for illumination source with $\lambda = 445 \text{ nm}$), there is no reliable vendor offering affordable filters for common microscopy applications. The double slit, used in Young's interference experiment, is a DIY part that we made using a laser cutter. This causes its inaccessibility for some of the users, although a home-made version produced by cutting an aluminium foil with a razor blade is also possible.

In the near future, we plan to focus on bringing the functional model of the FullBOX to a state of a prototype. This compilation provides the equipment for common microscopy methods and when properly assembled and prepared, the experiments can be demonstrated out of the box within a few minutes [81]. It is compact, hence portable, and can be taken to the field or stored for occasional use. The FullBOX is a complex yet uncomplicated example of everything the UC2 toolbox has to offer.

4.1.2 SimpleBOX and MiniBOX

Target group: Secondary and high-school pupils, ray optics experiments

Before the introduction of TheBOX, there was an independent attempt to provide simple educational experiments. In November 2018, I designed the set of four cubes in Fig. 4.3a that could be used to build the two classical telescopes, Keplerian and Galilean. This pocket-sized experiment set turned out to be very valuable as a portable showcase of the possibilities of the toolbox. The modules were accompanied by a manual (The Telescope Playground, Fig. 4.3b), which was the first attempt in designing a user manual, describing the experiments in a playful way, and making the experiments independent of a teacher.

The Telescope Playground and the need for a simplified version of TheBOX converged and the *SimpleBOX* was launched in December 2019 (Fig. 4.4). It contained eleven modules that were only mechanical, including no electronics. Its development therefore relied on launching the lens cube (section 3.1.1) and the mechanical Z-stage (section 3.1.4). This was the first comprehensive set that did not rely on any software and it significantly decreased the entry level of the toolbox.

We optimized the SimpleBOX to provide equipment for the demonstration of experiments (see Tab. 4.1) included in the syllabus [82] shown when ray optics is taught in schools, between 7th and 12th grade. These experiments are in our project documentation often cumulatively called “Simple Experiments”.

The first feedback from secondary school pupils, during a Science Day in grammar school Bergschule, Apolda in February 2020 was positive. The modules of this box were then further optimized for easy handling and a certain level of robustness, necessary for school children (section. 3.1).

However, SimpleBOX and Simple Experiments might not be the best names. Before the BOX was developed, when only showing the telescopes, we have heard from a bachelor student: “You should not say that the experiment

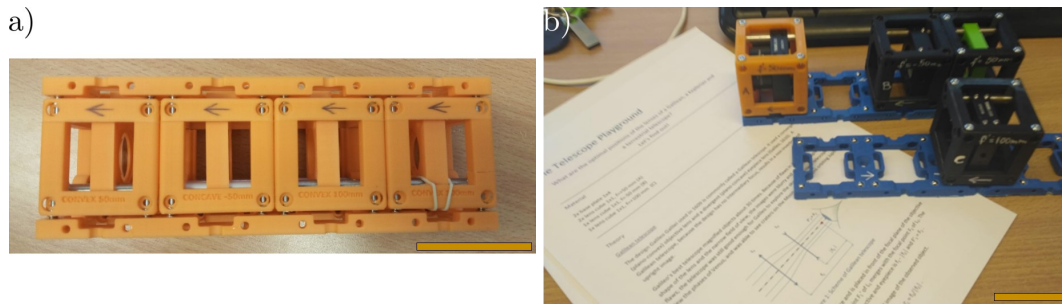


FIGURE 4.3: Pre-SimpleBOX experimental setups. a) The set of two baseplates and four cubes for showing two different types of telescopes, 3D-printed, version v0. b) The first version of the telescopes, using commercial cage plates, and an early version of the experiment manual. Scale bars: 50 mm.

are simple and easy, because people do not find them so easy, and they are discouraged and demotivated.” This is an interesting point of view to consider and we subsequently avoid such labeling in naming and presenting the toolbox.

Offering a comprehensive classroom kit raised awareness of the toolbox in the field of education. A call for workshops at a conference of the Gesellschaft Deutscher Naturforscher und Ärzte e.V. (GDNÄ) brought the opportunity and funding (from the Wilhelm und Else Heraeus-Stiftung) for preparing fifty copies of this kit. As mentioned in section 2.2.3, this enabled the development of the IM cube.

Scaling up the production made us consider the efficiency of the SimpleBOX. Additionally, we wanted to lower the price, since this is important for bringing the toolbox into public schools. Therefore, we set the goal as demonstrating the same experiments with the least possible amount of modules, the simplest version of those modules, and the cheapest components. See Tab. 4.2 to compare which modules were excluded. Tab. 4.1 shows that the same experiments were included. The *MiniBOX* design, introduced in the 3DP version even before the first IM cubes arrived, was the answer (Fig. 4.5a).

The 3DP inserts were adapted to the IM cubes and these together were implemented in the *MiniBOX* (Fig. 4.5b). We built 18 copies of this *MiniBOX* functional model and it was tested in our workshops, mainly for distance learning. Find the details in section 4.3.1.

This version suffered from two main issues. Firstly, the Z-stage caused uneasiness among the users. They often reported it seems broken, even though it was not, and even after an instructive video [83] or a direct explanation in a video call, they were unsure on how to use it, reporting that is broken, not working, and cannot be used. The second issue was sourcing the lenses. It

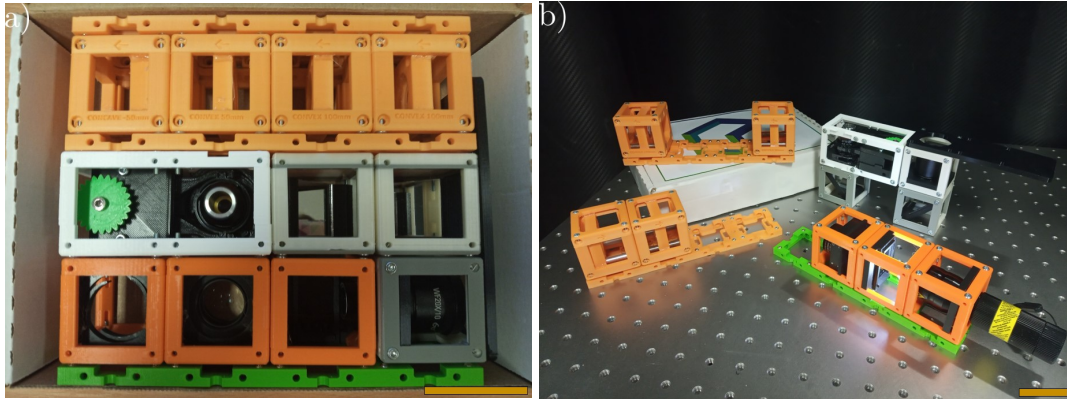


FIGURE 4.4: The SimpleBOX, version v2. a) The first comprehensive kit. b) Showcase of some of the included experiments. Left to right: Galilean telescope, Keplerian telescope, Smartphone Microscope, and a projector. Scale bars: 50 mm.

would be easy to equip the toolbox with quality lenses for around 20€ per piece, but that would increase the material costs of the MiniBOX too much.

There were four lenses needed per one MiniBOX. In the first version, there were three convex lenses, one 100 mm-lens (a lens with $f = 100$ mm) and two 40 mm-lenses. These were supplied by the online shop optikbaukasten.de [84] for 5.89€ per piece. The experiments were planned for 50 mm-lenses, matching the 50 mm cube pitch, but those were unavailable for a low price, and we chose the mentioned lenses and supplier due to their availability, while ensuring that the experiments could still be performed. However, due to long term low supply capacities, the supplier switched to delivering only to companies and no private customers, which made this source unsuitable according to the demands in section 2.3.2. The negative 50 mm-lens was also difficult to find and we turned to Thorlabs, Inc., which provided a fitting lens but for the price of 18.99€ per piece.

We found an alternative in Ajax Scientific Ltd [85], a Canadian company that was able to provide the desired lenses for a low price and, as an additional benefit, in large amounts (2.26 – 2.92€ per lens). The shipping costs are higher than for a German company but the overall benefits are significant. The lenses have the diameter of 38 mm, thus they offer a larger field of view, compared to the previously used one inch lenses. The originally planned focal lengths (convex: 100 mm, 50 mm, concave: 50 mm) belong to the standard assortment of this company. The MiniBOX inserts were updated for those, which was no issue thanks to the parametric lens holder from section 3.3.

With all external components optimized, we turned our focus on the hardware. At the same time, we got the opportunity to equip the out-of-school

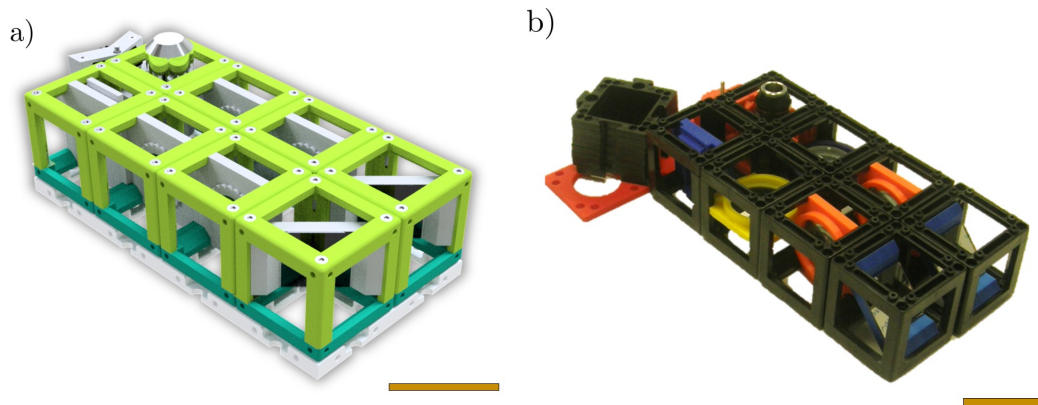


FIGURE 4.5: The MiniBOX. a) Rendering of a version v2 with a 4×2 baseplate. b) The first MiniBOX with IM cubes and baseplates and 3DP inserts. Scale bars: 50 mm.

STEM education centers (Schülerforschungszentren Thüringen (SFZ), supervised by the Stiftung für Technologie, Innovation und Forschung Thüringen (STIFT)) with in total 300 MiniBOXes. 3D-printing the inserts for one MiniBOX took around 12 hours with the Prusa i3 MK3S. This was doable for the fifty boxes for the GNDÄ assembly, but limiting for 300 of those. Cutting down the production time became crucial.

As described in section 2.2.4, we chose laser cutting to replace 3D-printing. The production time of this set of inserts (details in section 3.2) decreased to less than 10 minutes (for a single colour of all the inserts). The first prototype is shown in Fig. 4.6a. The unpopular Z-stage was replaced by the objective holder, which again lowered the entry barrier. Laser cutting also enabled the development of the MiniBOX packaging.

Using the black IM cubes and transparent acrylic glass gave the MiniBOX a very minimalist look. Transparent acrylic glass is also the most available and the cheapest one. But to distinguish between the lenses of the different focal lengths, we decided to use additional three colours of the acrylic. Each focal length was assigned an insert colour: yellow for 100 mm-convex lens, orange for 50 mm-convex lens, and blue for 50 mm-concave lens. A similar colour scheme was previously used for 3D-printing the first fifty boxes, due to the availability of the PLA filaments. This increased the laser cutting time to about 30 minutes per box and slightly increased the price of the lens holders but it made it very user-friendly. The colour scheme is not yet implemented in the MiniBOX booklet (appendix B) but it can be easily added when the colours are confirmed for mass production. It is debatable whether the transparent material is optimal for optics. On the level of experiments provided by the



FIGURE 4.6: MiniBOX prototypes. a) Early prototype without distinction between the lenses. b) Final prototype in proposed packaging. Scale bars: 50 mm.

MiniBOX, it is not an issue. For advanced applications, it is yet to be tested with the end users and the balance of price and performance has to be found.

The latest prototype is in Fig. 4.6b. The production of a single copy takes less than one hour and could be highly optimized for mass production. For the future product we decided to limit the amount of non-recyclable materials to the toolbox parts and not to add any unnecessary plastic packaging. The box is therefore padded by a folded paper structure. The MiniBOX, including its housing, could be offered assembled or as a building kit.

The two versions of the functional model and the prototype are compared in Tab. 4.3 in terms of workload, time to produce them, and price. At closer look, it is obvious that the combination of IM cubes and LC inserts is optimal, from the currently accessible options, for the following reasons:

- **Number of parts:** The complexity of the BOX is defined here by the number of parts necessary for its assembly. The IM cubes have a significant advantage here, since they do not require any assembly, just placing the insert inside. The IM components are included in the external parts, since their production is outsourced. What largely increases the amount of parts is the need for screws and nuts for the assembly of the LC inserts. This presents a slight advantage of the IM+3DP version over the IM+LC one but it is balanced by winning in time.
- **Manufacturing and assembly time:** Here, no parallelization of different production methods or production and assembly is considered, to provide an overview of the complete time. This shows where the main disadvantage of 3D-printing lies. The manufacturing time (sum of machine and assembly time) is $25\times$ longer than in the case of the IM+LC

MiniBOX version	3DP	IM+3DP	IM+LC
Amount of assembly parts	198	46	94
External parts	158	30	70
Produced parts	40	16	24
Manufacturing time	38h25min	14h10min	1h30min
Machine time	34h55min	11h55min	0h45min
Assembly time	3h30min	2h15min	0h45min
Manufacturing costs	146.90€	81.80€	24.50€
Material costs	40.69€	62.59€	66.84€
External parts	32.89€	59.14€	63.38€
Produced parts	7.80€	3.45€	3.46€
Total costs	187.59€	144.39€	91.34€

TABLE 4.3: MiniBOX version comparison. 3DP: Fully 3D-printed functional model. IM+3DP: Functional model, combination of injection-moulded cubes and 3DP inserts. IM+LC: Prototype, combination of IM cubes and laser-cut inserts. Manufacturing costs include running cost of the machines and labour costs. Details of the calculation are in appendix D.

MiniBOX. Given that the labour, hence assembly time, is very costly, it confirms why this is a method for prototyping but not production. Assembly time of IM and 3DP cube is compared in [86]. We include 15 minutes for general preparations in the assembly time calculation.

- **Total costs:** The comparison of the material price shows the benefit of 3D-printing, since the filaments are cheaper than plexiglass and significantly cheaper than the currently produced IM cubes. However, 3D-printing does not reduce the price even by 10% and most of its cost is given by the labour for the long manufacturing time.

The detailed calculation with sources is in appendix D, with a complete list of parts, the estimated costs of 3D-printing, laser cutting, and labour. For the production, the costs of 3D-printers and of a laser cutter are considered using an amortization estimate. The advantage of the IM+LC MiniBOX in terms of manufacturing time is so significant that although the laser cutter is much more expensive than the 3D-printed (see appendix D), the total costs are still significantly lower.

It is important to note that the prototype was optimized with a focus on low price and reduced workload. The benchmark to accept a design was whether it was possible to realize all the experiments assigned in Tab. 4.1. The educational MiniBOX does not aim at any particular performance parameter, such as imaging quality, but on covering the syllabus, lowering the entry barrier, and minimizing the production costs and efforts. An upgrade might

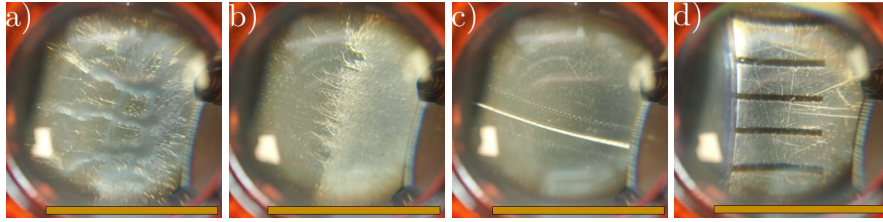


FIGURE 4.7: Images taken using the Smartphone Microscope built from the MiniBOX prototype. Illumination: Ceiling light, Smartphone: Xiaomi Redmi 6. Images a) - c): Home-made samples prepared using sticky tape. a) Fabric. b) Edge of a paper. c) Human hair. d) Ruler for scale. Scale bars: 5 mm.

be considered, a version that resembles more the SimpleBOX, depending on the first market feedback.

Alongside the development of the hardware, we designed the MiniBOX booklet, which was necessary for testing as stated in section 2.3.1. This manual aims at the 7th - 12th grade pupils and guides them through the experiments of the MiniBOX and explains the underlying theory. Note that it includes in total 12 experimental pages, in order to build up the more advanced systems in a logical way. We developed it together with the SFZ witelo e.V. Jena, to ensure that the level fits the application. It is written in German, for the purpose of local testing and its preliminary English and German versions are also available in the repository [7]. The booklet is attached as appendix B.

Fig. 4.7 shows images taken using the Smartphone Microscope built from the MiniBOX prototype, results of the final experiment of the MiniBOX booklet. The quality does not reach the level of a standard school microscope, but it is important to emphasize that this is also not the aim. The system offers all the ray optics experiments of the secondary and high school level and a comprehensive path through all of them, from the basic (effects of a lens) to advanced (light microscope).

4.1.3 PolarBOX

Target group: High-school and university students, experiments regarding the polarization of light

The *PolarBOX* is a set of modules designed to demonstrate the experiments that show the polarization properties of light. It was built using the cube v2 and a preview is given in Fig. 4.8. The list of the polarization experiments

PolarBOX experiments
Crossed Polarizers
Three Polarizers
Polarization Experiment using Optically Active Solution
Circular Polarizer
Brewster Angle Experiment (Polarization by Reflection)
Many Microscope Slides Experiment (Polarization by Transmission)
Stress Birefringence Experiment
Newton's Rings Experiment (not polarization but developed along)

TABLE 4.4: Experiments developed specially for the PolarBOX.

(according to their naming in GitHub) is in Tab. 4.4. The necessary modules are listed in Tab. 4.2.

These demonstrations enriched the list of UC2 applications and new modules and sources of components, such as polarization filters, were added to the repository. Polarization is an important sub-chapter of optics and the potential implementation of polarization microscopy using the toolbox is very attractive. It is currently at the stage of a functional model.

The further aim is to structure the educational branch of the UC2 project into chapters resembling the school syllabus. This means having a basic kit (the MiniBOX) as a starter pack and then offer add-ons for the other topics. The content of the upgrade BOXes shall be optimized and always build upon the basic kit. The PolarBOX was the first explored topic for the potential add-on BOX and designing the structure and means of upgrading the basic set lies in the future.

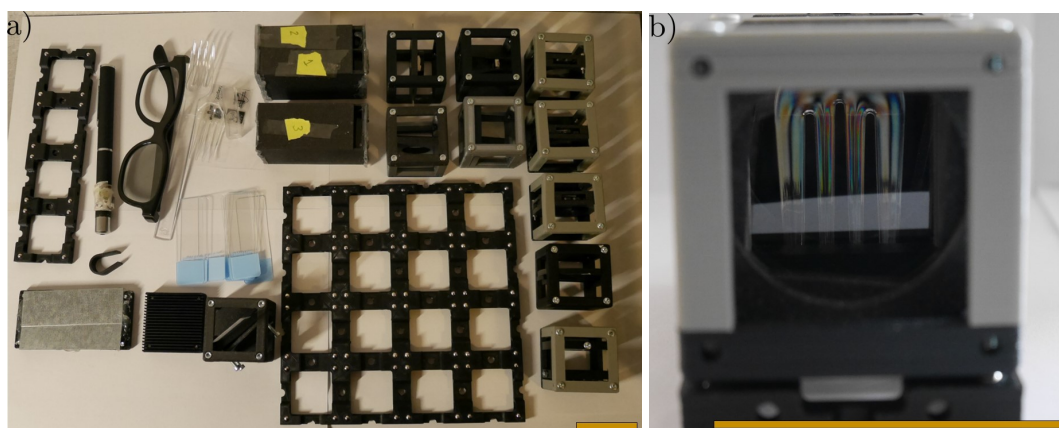


FIGURE 4.8: The PolarBOX, cubes version v2. a) All modules included in the first functional model. b) Experiment example: Stress Birefringence. Scale bars: 50 mm.

4.1.4 CourseBOX

Target group: University students, optical microscopy alignment, Fourier optics, optics courses at imaging facilities

In the beginning of 2020 we were approached by Dr. Sebastian Bundschuh from the Light Microscopy facility of the Max Planck Institute of Molecular Cell Biology and Genetics (MPI-CBG) from Dresden and asked to collaborate on the development of an educational kit for the practical part of their microscopy course. Initially, because it was developed for a Core facility, this set was called *CoreBOX* [7], but it was soon renamed to *CourseBOX*, to indicate that it serves for the purposes of light microscopy courses.

The initial version of the CourseBOX in Fig. 4.9 was built using the v2 cubes. The system provided a hands-on experience on the alignment of a simple and compound microscope with direct or Köhler illumination. All the conjugate planes were accessible and it was possible to image the back focal plane and the image plane simultaneously. In terms of optical design it relied on finite conjugate systems. The setup contained seven lenses of six different focal lengths. This was very inconvenient for reproducing the system but also for the alignment procedure.

Therefore, we proceeded with developing an infinity-optics version. We focused on providing two, partially overlapping, experimental setups. First of them is the Compound Microscope with Köhler Illumination and access to all the conjugate planes. Fig. 4.10 shows the second one, a refined version of the Abbe Diffraction Experiment, also demonstrated in [87]. Note that due to limited space the side arm contains an infinite conjugate system but not a 4F system (as introduced in section 1.2.3).

This Compound Microscope setup was arranged in accordance with the Optical Alignment and Microscopy Practical Course from Dr. Noah Russell (from the Practical Course on Advanced Optical Microscopy for Cell Biology held in Plymouth, UK [88]), with the goal to use this in a practical course at the Friedrich-Schiller-University Jena that follows this manual. The original experiment is built on optical rails using standard components mounted on optical posts. The alignment has all possible degrees of freedom, which, in the time frame given for the course, often results in the students not being able to finish or achieve a satisfactory result. Due to that, the learning output is lowered, because instead of observing the optical principles and effects most time is spent on the repetitive alignment procedure.

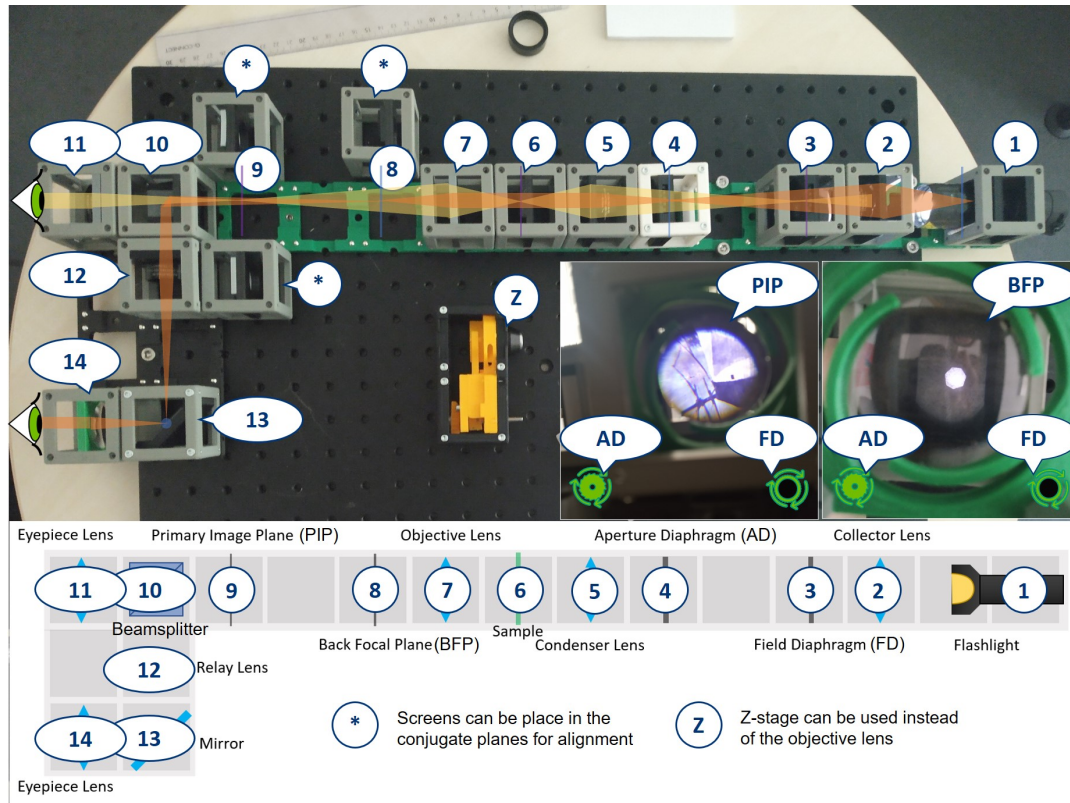


FIGURE 4.9: From the CourseBOX Alignment Procedure (Finite Optics). Through the eyepieces (marked 11 and 14) both sets of conjugate planes can be seen simultaneously. Showing the primary image plane (PIP) and the back focal plane (BFP) as viewed through the eyepieces [7]. Aperture set of conjugate planes is in blue, corresponding light path in orange. Field set of conjugate planes is in purple, corresponding light path in yellow.

The optical design of the “Plymouth Experiment” had to be translated into the modular design. The original microscope is built using lenses with focal lengths that would not fit the pitch of the modules. To simplify the alignment, we decided to use only convex lenses with focal length of 50 mm (white lens modules in Fig. 4.10) and 100 mm (blue lens modules in Fig. 4.10). This way, no magnification is introduced in the illumination path and only a two-fold magnification is observable in the imaging path. This is however no issue for the educational purpose. The Raspberry Pi camera module was used for image acquisition.

Translating an existing experiment into the UC2 toolbox can be troublesome, due to the size limitation. Especially the focal lengths cannot be arbitrarily exchanged and in the design it might happen that planes, freely accessible in an optical bench or breadboard system, become inaccessible and therefore proper alignment is hindered. As a matter of good practice for designing an educational toolkit with UC2, we recommend to keep the optical principles,

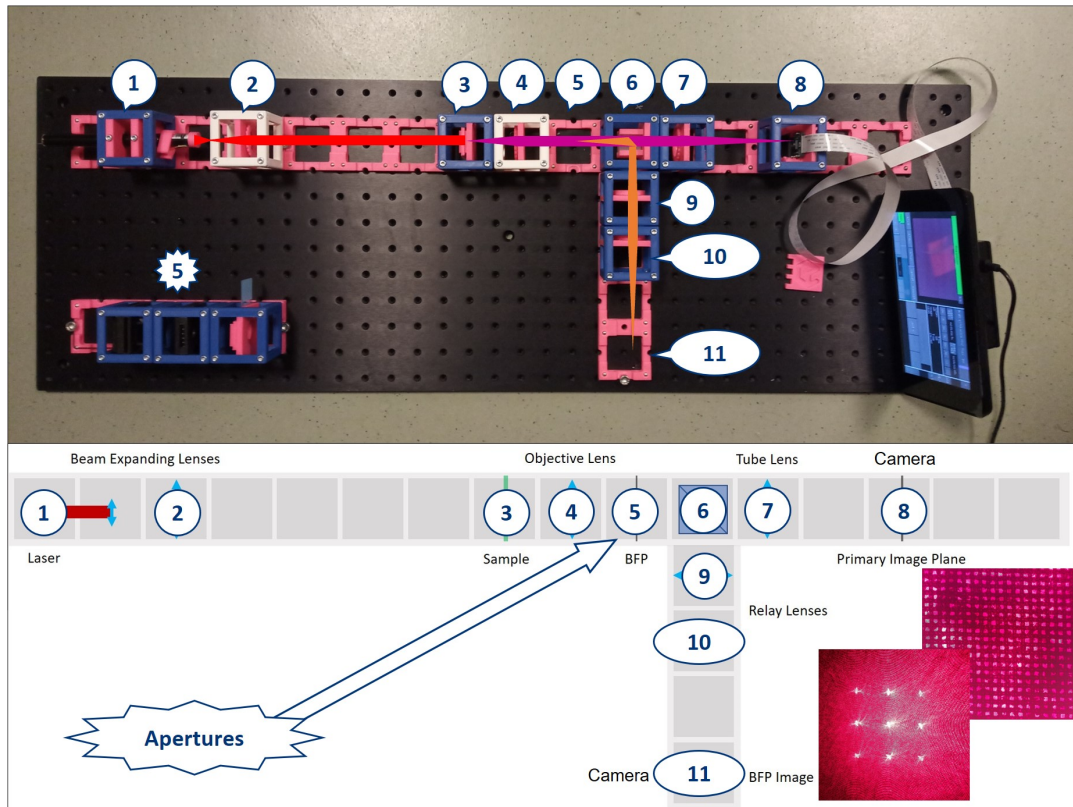


FIGURE 4.10: From the CourseBOX: Light Microscopy and Optical Alignment (Infinity Optics). The Abbe Diffraction Experiment. Showing the primary image and the back focal plane image, bottom right [7]. Light paths: Illumination - red, imaging the sample - purple, imaging the back focal plane - orange.

which are to be taught with it, in the foreground and adapt the hardware to that, even if that means keeping only the basic properties or lowering magnification, like in the case above.

The CourseBOX could eventually also be an add-on of the MiniBOX. For one semester of the practical course, during the university closure, we adapted the “Plymouth Experiment” for distance learning, using the MiniBOXes we had at hand (See Tab. 4.5). The equipment could not cover the experiment in its full extend, but in the adapted version the key principles were taught and we provided a hands-on experience when there was no other access to it. Potentially, by adding only four extra modules (two circular apertures, flashlight, and one extra lens), the MiniBOX can be upgraded for showing the Compound Microscope Experiment.

The current state of the CourseBOX is a functional model, undergoing testing in the classroom. It is to be considered whether to design the prototype from the current system or redesign the system as an add-on of the MiniBOX.

4.2 Educational microscopes

The comprehensive educational kits can serve as a first introduction to the toolbox and can be used to teach the basic theory or state-of-the art microscopy methods. As the next step, we propose project-based courses in which the existing hardware is used as a tool to easily develop the ideas of the students. Here we present two successful examples of such implementation in existing high school and university courses.

4.2.1 The Light Sheet Microscope

The Light Sheet Microscope is probably our most successful educational microscope. Since its first implementation in the International Day of Light workshop, it brought countless “Wow” and “Aha” moments. We demonstrated it in most of the events listed in section 4.3.1 and its success can be best illustrated by quoting a participant from the University of Oslo: “I work with a light sheet microscope so often for so long but now I finally understand how it works.”

The Ultramicroscopy principle, now called the light sheet principle is known for over a century [89] but it gained attention mostly in the last decade, due to the use of modern methods and advanced image processing. The Selective Plane Illumination Microscopy (SPIM), or Light Sheet Fluorescent Microscopy (LSFM), is now a popular method for imaging volumetric biological samples. The commercially available systems are often not fulfilling the needs of the scientist [90] and therefore there are many open-source and DIY approaches [91].

Our optical design is inspired by the OpenSPIM [39] setup. OpenSPIM is a platform that offers detailed instructions for the assembly and operation of a basic SPIM system and helps to build a community to collaboratively improve it. It is however a professional device, requiring a larger investment and a skilled researcher to build it. With our light sheet system, we aimed for a device that anyone could reproduce, even at home. The approach we chose to this system was very minimalist. It uses only eight modules (see Fig. 4.11) and relies on cheap components, with the overall material costs around 400€. The current version occupies an area of 5×4 baseplate units, hence $250 \times 200 \text{ mm}^2$. The design started in the v0 version (Fig. 4.12a) and every module and the whole system was optimized to yield the current state in Fig. 4.12b, which uses the IM cubes.

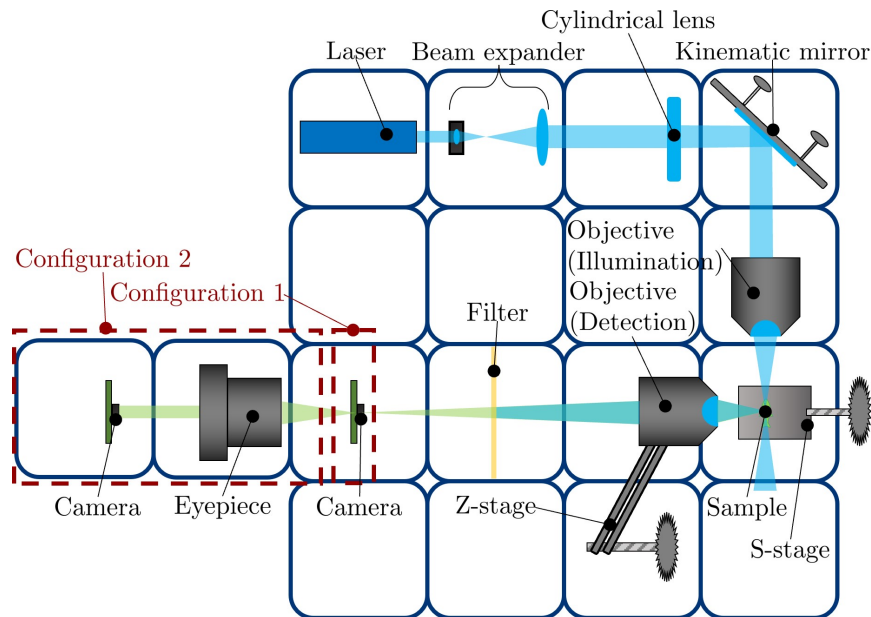


FIGURE 4.11: Optical scheme of the Light Sheet Microscope. Configuration 1: Simple microscope detection path. Configuration 2: Compound microscope detection path. One square corresponds to a baseplate unit of $50 \times 50 \text{ mm}^2$.

The scheme of the optical design is in Fig. 4.11. The illumination path is on the top and right side. We use a blue laser pointer ($\lambda = 445 \text{ nm}$, 5 mW , Laserlands®Store) as a light source. The light is expanded by a telescope, in the beam expander module. This comprises of a smartphone camera lens (Apple, iPhone 5, $\text{NA} = 0.24$, $f = 3.2 \text{ mm}$, or alike, adjustable) and a convex lens ($f = 20 \text{ mm}$, also tested and approved $f = 26.5 \text{ mm}$, due to the availability of the suppliers for companies or private users). The laser light is focused by the smartphone lens and collimated by the convex lens to a beam diameter of roughly 10 mm .

The beam is focused by a cylindrical lens into a line profile, parallel to the plane of the paper in the scheme, horizontal in the setup. These lenses are difficult to obtain for a reasonable price and originally we relied on the lens with $f = 63 \text{ mm}$ from Comar Optics for 60€ . To improve accessibility, we replaced it with a 30 mm long piece of a acrylic glass half-rod, available from eBay. The rod has a diameter of 15 mm , hence much shorter focal length, but it can be aligned to produce a light sheet in the sample area.

The light is then reflected by the mirror in the kinematic mirror (45°) module. This has two functions. Firstly, folding the beam yields the system compact. Secondly, the kinematic mechanism allows alignment of the light sheet onto the plane focused by the detection objective. In the basic version a self-adhesive mirror is used, the size of $30 \times 30 \text{ mm}^2$, which for 3.50€ comes in a set of 45 pieces for a DIY mirror mosaic (Rayher Hobby GmbH). These

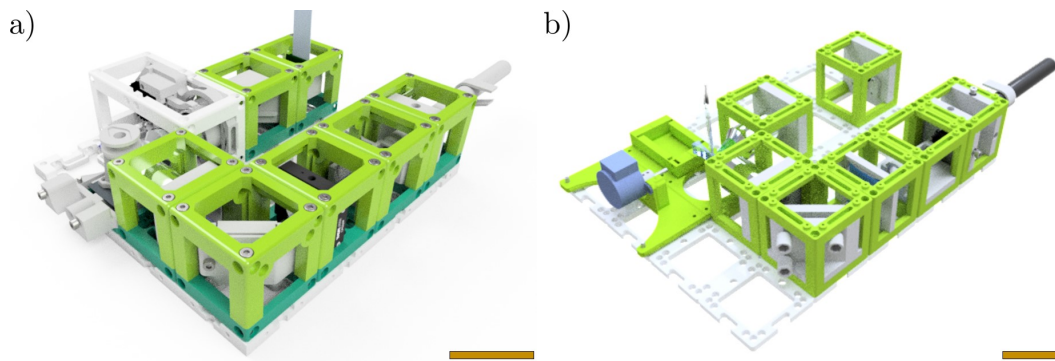


FIGURE 4.12: Renderings of the Light Sheet Microscope. a) First setup, version v0. b) Latest version, using IM cubes. Scale bars: 50 mm.

mirrors are very accessible, but at the cost of degraded optical performance. The back-coated mirror reflects the incoming light twice and this produces a shadow light sheet in the sample area, in addition to the one that is intended for illumination. Therefore, for performance measurements and data acquisition, a front-coated silver mirror was used instead. The PF10-03-P01 scientific-grade mirror from Thorlabs, Inc. costs 48.70€ per piece. For demonstrations for educational purposes (no data reconstruction involved), it was observed that the shadow light sheet is not a problem, especially in daylight conditions, using the $10\times$ objective in the detection path, and with the test sample (paper tissue) described below. The two alternatives are available and explained in the documentation and it is up to the user to choose a suitable one for their application.

Finally, the light sheet is focused by the illumination objective ($4\times$, $NA = 0.1$, Aliexpress) into the sample. The measured thickness of the light sheet was around $50\ \mu\text{m}$ with the 63 mm-cylindrical lens. This is comparable to the depth of field of the detection objective, therefore sectioning is possible.

The detection path consists of an objective ($4\times$, $NA = 0.1$ or $10\times$, $NA = 0.3$) mounted in a Z-stage and a Raspberry Pi camera (V2.1), forming a simple finite-corrected microscope (configuration 1 in Fig. 4.11). Behind the objective we place a piece of lighting filter, namely Lee 010 medium yellow. As shown in Fig. 4.12a, the use of a filter module was intended in the early version. But with the use of cheap filters, we omitted the module and the filter is simply placed in front of the camera or behind the objective.

Firstly, a section of the sample is focused on the camera, then the illuminating light sheet is aligned to that plane. In this case, the Raspberry Pi camera is without a lens, because a real image is produced by the finite-corrected objective. This is however not optimal, as the camera then produces artifacts

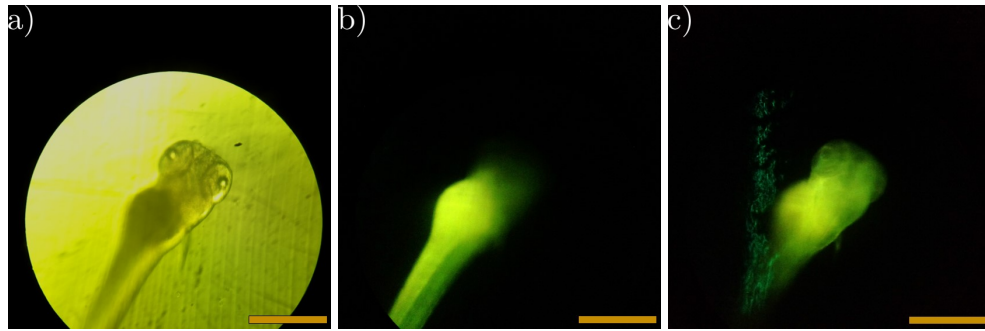


FIGURE 4.13: Images acquired using the UC2 Light Sheet Microscope, configuration 2. Imaging quality and sectioning properties achievable by an unskilled user. a) Bright field image of a Zebrafish embryo. b) Light sheet image, section through the spine. c) Light sheet image, section through the head. Light sheet thickness: $\approx 50 \mu\text{m}$. Scale bars: $100 \mu\text{m}$.

due to non-uniform colour response [92]. Therefore, for taking volumetric data of biological samples (Fig. 4.13), we used configuration 2 from Fig. 4.11. There, the intermediate image is further imaged to infinity using an eyepiece ($20\times$) and then focused on the camera chip by its inbuilt lens.

The light sheet is static, meaning it is aligned to the plane focused by the detection objective and the sample is scanned through it using the S-stage module (sample-stage). We initially, for the v0 system in Fig. 4.12a, experimented with a fluorescent sample prepared in a syringe filled with agarose, the object of interest being pollen or a Zebrafish embryo (transgenic line Tg(kdr:EGFP), fixed at 72 hours) such as the one shown in Fig. 4.13. But the long syringe was sensitive to vibrations, the sample preparation was time-demanding, and the samples did not last long. Thus we designed an S-stage for holding a standard microscope slide, shown in Fig. 4.12b. A 3D-printed water chamber can be placed in the position of the sample as well, to demonstrate the shape of the light sheet.

As a test sample for alignment and for demonstrations outside of the optical lab a single layer paper tissue was attached to a microscope slide and painted with a yellow highlighter pen (such as Stabilo Boss, Art. No. 70/24), see Fig 4.14. The yellow dye is fluorescent when illuminated with the 445 nm laser and bleaching was not observed. The slide is placed at roughly 45° with respect to both the illumination and detection path and thus when the sample moves through the light sheet, consequent sections of the tissue are seen. The tilted tissue sample appears to move through the field of view. Although this is no scientific sample, it is very powerful for the explanation of the light sheet principle, because the audience understands the relationship between

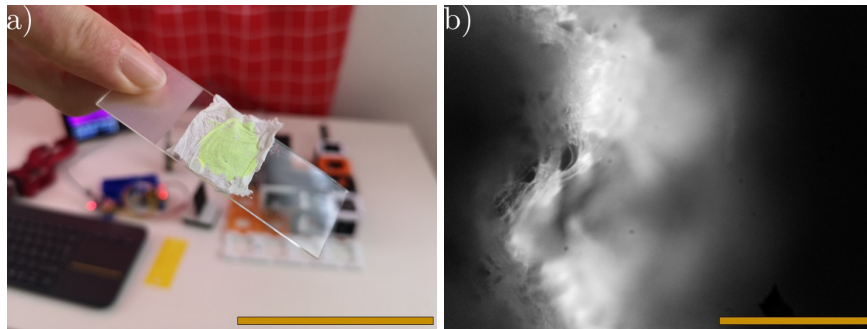


FIGURE 4.14: Test and alignment sample, single layer paper tissue attached to a microscope slide and painted with a yellow highlighter. a) The prepared sample [5]. Scale bar: 50 mm. b) The light sheet image of the sample, using configuration 1 of the microscope. Scale bar: $100\ \mu\text{m}$.

the sample object and the image on the screen and comprehends the observed effect immediately. The angle maintained by the sample stage is designed to be 50° w. r. t. the detection path, hence 40° w. r. t. the perpendicular illumination, to avoid a direct reflection from a cover slip in case of using one.

Fig. 4.15a shows the light sheet system in configuration 2 in the lab, as it was used for most experiments and testing. In Fig. 4.15b is the third possible configuration, which is particularly useful for public demonstrations. Here, the detection path is adapted for a smartphone, using a 45° -mirror module to divert the incoming light upwards into the eyepiece. A smartphone is then placed with its camera above the eyepiece to show the image. This configuration had limited stability using the v2 version. It was improved by switching to the v3 cubes (here combined), which enabled stable three-dimensional setups.

Both stages are equipped with a motor controlled via WiFi connection and a Z-stack of images can be acquired using the tomographic mode of the UC2-GUI. However, for public demonstrations, when using a low magnification detection objective, it is also possible to conveniently show the light sheet effects when moving the sample by hand.

The accessibility and reproducibility of the system is highly dependent on the documentation. In addition to the building instructions, as mentioned in section 3.5, we provide a detailed description of how to align this setup [7]. To bring the system to the tinkerers and show how low the entry level of microscopy can be, we took the opportunity to publish an article on this topic in the German MAKE Magazine [5]. The article features the explanation of the method and the instructions on how to build it at home. The procedure is also comprehensively documented in the UC2-GIT [7].

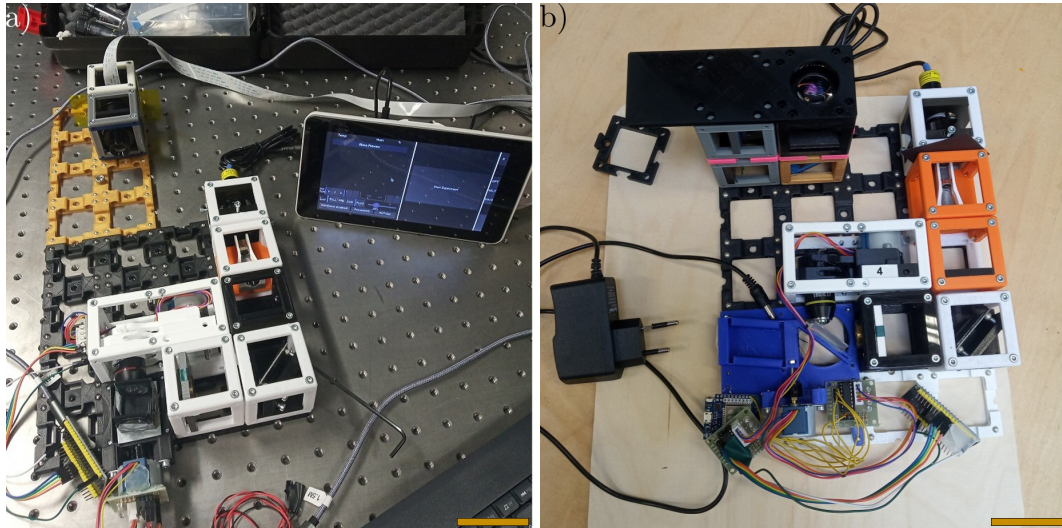


FIGURE 4.15: The Light Sheet Microscope implementations. a) Experimental setup in the optical lab used for image acquisition of Fig. 4.13, configuration 2, cubes version v2. b) Light sheet setup for a project-based course focused on the electronics improvement, configuration 3, cubes version v2 and v3. Scale bars: 50 mm.

The microscope in Fig. 4.15b was lend in October 2021 to the FabLab maker space of Hochschule Ruhr-West for a project-based course. A group of students worked on developing a better electronics control for it, to increase the user-friendliness of the ligh sheet system and hence its usability in education.

The UC2 Light Sheet Microscope was used purely for outreach and in the educational context. Thanks to the modular principle, the toolbox could also serve as a base of a scientific light sheet system. This offers a chance to close the gap between education and research and bring the advanced methods to a broader audience or their daily users who know them only as a black box.

4.2.2 The Smartphone Microscope

Nowadays, implementation of smartphones is very attractive for microscopy, because they are powerful computational devices with integrated high quality cameras, and because it is appealing to the users to take images with their own smartphone. The UC2 Smartphone Microscope developed from the Incubator-enclosed Microscope, which is a simple finite-corrected microscope consisting of an LED matrix, a sample holder, a Z-stage carrying an objective, mirror, and a camera, and which needs to employ a Raspberry Pi computer for image acquisition and setup control. By adding and extra mirror, an eyepiece, and a smartphone holder, the microscope is adapted for the use of a smartphone for imaging but also for direct observation of the sample through the eyepiece.

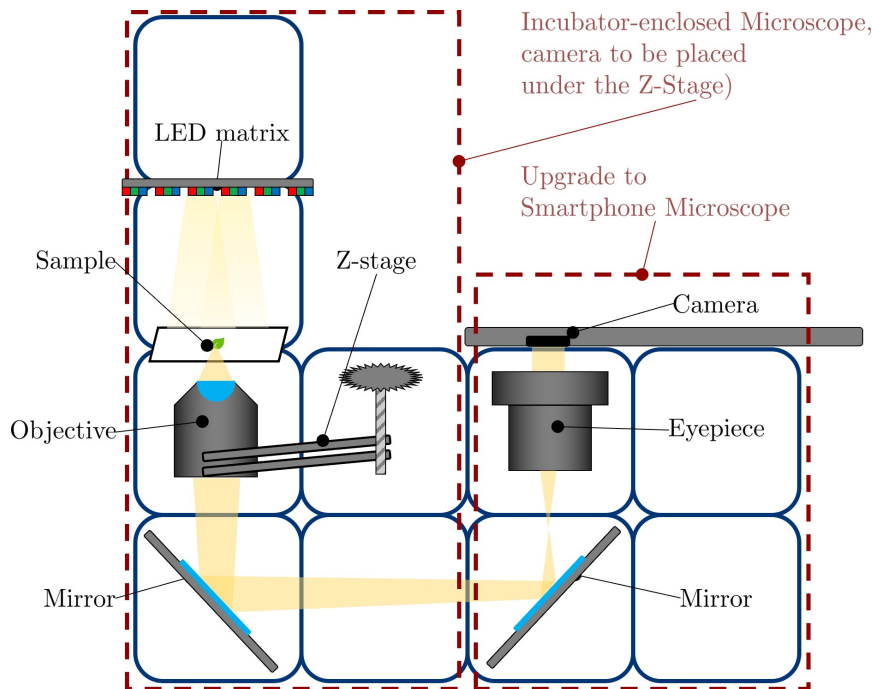


FIGURE 4.16: Optical scheme of the Smartphone Microscope, upgraded from the Incubator-enclosed Microscope. One square corresponds to a baseplate unit of $50 \times 50 \text{ mm}^2$.

See the basic scheme of the compound microscope in Fig. 4.16. It is an inverted microscope, which means that the sample, illuminated by the LED matrix, is placed above the objective, usually using $4\times$ or $10\times$ magnification. The light path is folded by reflecting from the two mirrors and the image is viewed through the eyepiece by the smartphone camera focused to infinity or alternatively by the naked eye. The microscope appears in two versions, a mechanical-only one, and one equipped with electronics for focusing and illumination. 2 – 3 empty cubes are used to increase the stability of the system.

The mechanical Smartphone Microscope is included in the MiniBOX. It can use either the mechanical Z-stage or the objective holder. There is no illumination source, but another smartphone, a flashlight, a desk lamp, or a ceiling light can be used. This is not optimal but using a light source is a potential obstacle for certification and approval to be used by children. However, in terms of design, it is no issue to add for example the LED module or LED matrix module to illuminate the sample.

Because of its attractiveness and approachable design, the Smartphone Microscope became a popular choice for student projects of local grammar schools (German: *Gymnasium*). The current version of the electronic one is mainly a result of two seminar projects (German: *Seminarfacharbeit*). This type of a project is very important in the final stage of the Thuringian high

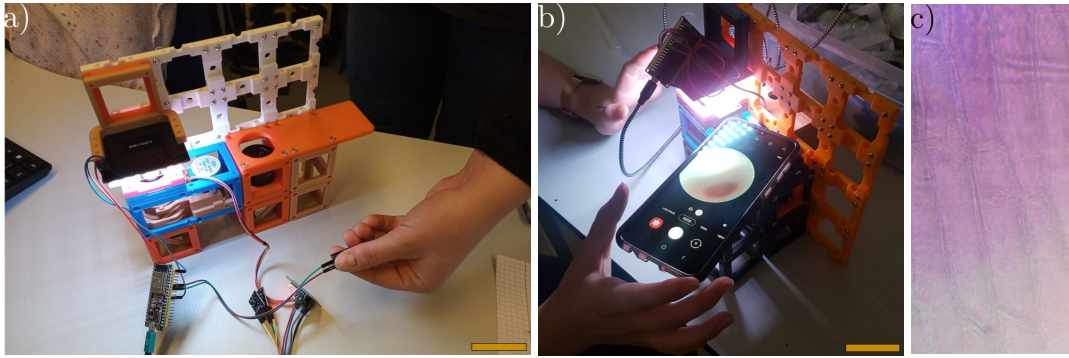


FIGURE 4.17: The Smartphone Microscope results of the seminar project at the KLG. a) Final design with buttons for electronics control. b) The microscope during the experiments in the classroom. Scale bars: 50 mm. c) Image of tomato cells acquired in the classroom testing. Scale unknown. Images provided by the students.

school education (also in other federal states) and these successful examples prove the value of the UC2 toolbox for schools.

The first project, carried out at the Königin-Luise-Gymnasium (KLG) in Erfurt, focused on implementing the Smartphone Microscope for the practical exercises of the biology classes, as an alternative to the standard school microscopes. Before that the electronics could be controlled either from the GUI installed on a Raspberry Pi, which was inefficient when using the smartphone for image acquisition, or from a UC2 Android App, which was in an early development stage and therefore could not provide a stable solution. To bring the microscope into the classroom, the electronics control had to be simplified.

The controlling software was replaced by simple buttons. The button connected to the LED matrix controlled the illumination intensity by going through a loop of turning on four, sixteen, sixty-four, or none of the LEDs. This is not optimal since it also influences the size of illuminating area and the illumination angle but it is acceptable for this application. The Z-stage was controlled by two buttons, one for the upwards and one for the downwards direction. This was intuitive and straightforward for pupils of all ages when explained in the classroom. A control module was added to the back side of the microscope, where the buttons were mounted and a respective descriptions indicated their purpose. The button-controlled Smartphone Microscope, without the control module, cubes version v2, is shown in Fig. 4.17a.

Five copies of the improved microscope were build by the authors of the seminar project and tested in comparison with the standard school microscopes. In total 35 pupils, from 7th, 10th, and 11th grade, had the chance to test and evaluate it. The testing had to be reduced with respect to the original plan

due to the pandemic situation and closing of schools. Each pupil observed the test sample, freshly prepared tomato cells on a glass slide, using both the standard school microscope and the 3D-printed Smartphone Microscope.

Despite the fact that almost 75% of the students reported troubles when working with the Smartphone Microscope, the general feedback was very positive, the pupils were from the beginning curious about the new method and enjoyed trying it out. The issues were related to stability, alignment, and the provisional look caused by the cables that loosely connected the electronic modules and the control module. As an advantage over the standard equipment they reported the use of a smartphone for image acquisition and that the 3D-printed microscope was “more fun”. The teachers considered the Smartphone Microscope to be an enrichment of science teaching in the context of digitization and supported its further use, supposed that the handling issues would be solved. These results were presented by the students.

The first “Seminarfacharbeit” was submitted to the KLG in school year 2020/2021 under the title “Etablierung des innovativen Smartphone-Mikroskops im Schulunterricht” (Establishing the innovative Smartphone Microscope in the classroom) by Sophie Gießmann, Maura Luise Holz, and Charlotte Luise Schütze. We then added their results to our GitHub and the next project group could continue working on the improvement of the microscope from there.

The second project at the Carl-Zeiss-Gymnasium went in the direction of more complex hardware improvement. The students chose three issues that they wanted to overcome: integration the electronics control in a more professional-looking way, possibility of changing the magnification, and precise sample positioning in the X- and Y-direction.

Using the openSCAD files provided in the UC2 repository, they were able to develop their own modules and combine them with the available ones. Following the Modular Developer Kit they could also design parts that fit to the system but not inside a cube. Within the modular configuration and simple optical design, the students could implement their ideas easily.

For changing the magnification, standard microscopes carry a revolving nosepiece with two or more objectives. The school microscopes are typically equipped with objectives with $4\times$, $10\times$, and $40\times$ magnification, and a $10\times$ eyepiece. Because the UC2 motorized Z-stage ($4\times$ objective used here) is a rather complex module, it was easier for the students to design a revolving eyepiece holder instead, visible in the green frame in Fig. 4.18a, carrying eyepieces with $10\times$ and $20\times$ magnification. This unusual solution shows how much the design supports creativity and allows different approaches.

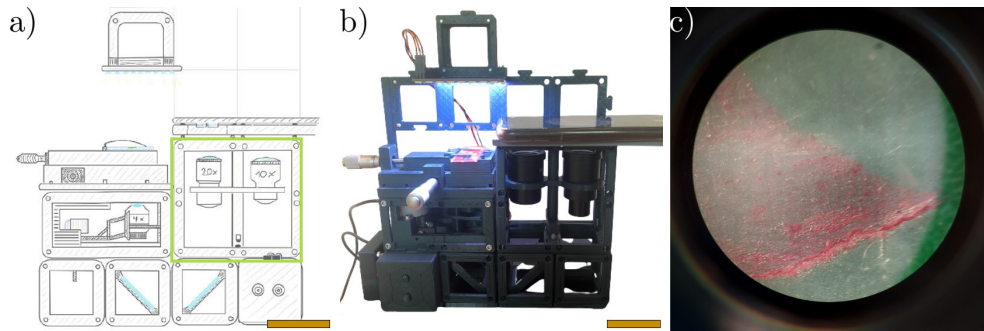


FIGURE 4.18: The Smartphone Microscope results of the seminar project at the CZG. a) Sketch of the proposed hardware improvements. b) Final setup. Scale bars: 50 mm. c) Image of a ginger section acquired using the improved microscope. Scale unknown. Images provided by the students.

The new X,Y -stage design is simple yet precise and robust. It relies on micrometer screws and has three layers, a base that is mounted on the Z -stage, a middle one that moves along one axis, and a top one that moves in the perpendicular direction. The micrometer screw pushes its plate in one direction and magnets are used to maintain the contact between the screw and the plate, to enable pulling it back. The plates move along 3D-printed dovetail rails, which are commonly used in optical rails [93].

Electronics modules were designed to stand on the back side of the microscope. Two switch plates were added to the front of it, one for illumination (one button) and one for focusing (two buttons). Together with a number of smaller optimizations, this significantly improved the handling of the microscope.

The results of this project will again be used to update the Smartphone Microscope in the UC2-GIT, to offer the benefits of the improved system to the education community. Additionally, the school considers long-term implementation of the microscope in their classes.

The second “Seminarfacharbeit” was submitted to the CZG Jena in school year 2021/2022 under the title “Erstellen eines Mikroskops mit Hilfe des 3D-Drucks” (Creating a microscope using 3D-printing) by Gregor Bolze, Kai Diegel, and Felix Geiler.

Thanks to the UC2 toolbox with its documentation, the Smartphone Microscope could be improved and implemented by high school students for their fellow students. Furthermore, the second project built upon the results of the first one, which demonstrates the power of the open-source hardware development. The UC2 Smartphone Microscope is now a simple and practical tool, adjusted by the students themselves for the high school level education.

4.3 Testing

The presented hardware and documentation were developed in close contact with the target audience. This ensured the validity of the results. The testing process was not only iterative but also the flow of the ideas was bi-directional. Novel ideas coming from the users were also considered and implemented when proved as beneficial.

4.3.1 Workshops and courses

The educational boxes were developed for and with the end users. The development of the MiniBOX prototype and the whole concept of the BOXes would not have been possible without the input from them. We have organized workshops and courses, and demonstrated the toolbox to the public. The educational kits and applications were iteratively improved using the user feedback. Thanks to the comprehensive approach, we were able to engineer a useful and user-friendly tool for teaching. Find the complete overview of the events in Tab. 4.5.

Some of these events were more important for the development and the findings are listed below the table. This is because they were milestones for testing a given version of the modules, the BOXes, or a certain approach. They were beneficial for further development of the toolbox and their dates are in bold letters in the table.

Date	Location	Toolbox	Description
09/2018	Lichtwerkstatt, Jena	In-Line Holography	First public workshop, building a system from scratch
05/2019	Lichtwerkstatt, Jena	Light Sheet Microscope	Hackathon on the International Day of Light, building a system from scratch
07/2019	Lichtwerkstatt, Jena	TheBOX development	Project of the Photonik-Akademie Innovation camp
09/2019	Janelia Research Campus, USA	FullBOX	First workshop using the Full-BOX and the cubes version v2

Date	Location	Toolbox	Description
01/2020	Carl-Zeiss-Gymnasium, Jena	Smartphone Microscope	Seminary project: Building a UC2 Smartphone Microscope, development of an illumination-control app (09/2018 - 01/2020)
01/2020	Oslo NorMIC Imaging Platform, Norway	FullBOX	Comprehensive two-day microscopy workshop
02/2020	Gymnasium Bergschule Apolda	SimpleBOX	Science day, first use of the SimpleBOX on high-school level
03/2020	Trends in Microscopy Spring School, Münsingen	FullBOX	First workshops given without the presence of anyone from the UC2 core team
03/2020	Cambridge Science Festival, London, UK	SimpleBOX	Public interactive demonstration
04/2020	Antananarivo, Madagascar	SimpleBOX	Workshop for the local STEM initiative
06/2020	Stockholm, Sweden	FullBOX	Microscope development using UC2 toolbox
06/2020	Prague, Czech Republic	FullBOX, SimpleBOX	Workshop for university students of biology, workshop for a local high school
09/2020	GNDÄ conference, Würzburg	MiniBOX	Student workshop on building their own MiniBOX with provided components, first time using the IM cubes
10/2020	Zoology department, FSU Jena	FullBOX, MiniBOX	First in-person workshop using the IM cubes and the MiniBOX
11/2020	Secondary/high schools, Jena	MiniBOX	IPHT Science cart visiting schools

Date	Location	Toolbox	Description
<i>01/2021</i>	Königin-Luise-Gymnasium, Erfurt	Smartphone Microscope	Seminary project: UC2 Smartphone Microscope in high-school level Biology classes (09/2019 - 01/2021)
<i>01/2021</i>	Montessori School, Jena	Incubator-enclosed Microscope	Seminary project: Detecting fluorescent microplastics using a UC2 microscope (09/2019 - 01/2021)
03/2021	SFZ witelo e.V. holiday workshop, online	MiniBOX	First hands-on distance education workshop (Jena)
04/2021	Microverse Imaging Center, online	MiniBOX	Distance education hands-on session (Jena)
05/2021	Practical Course, Medical Photonics program, FSU Jena	MiniBOX	First implementation of the toolbox in a standard course, distance education (05/2021 - 08/2021)
09/2021	FabLab HRW, Bottrop	FullBOX, MiniBOX	UC2 introduction for a project-based course, the Light Sheet Microscope selected for further collaboration
<i>01/2022</i>	Carl-Zeiss-Gymnasium, Jena	Smartphone Microscope	Seminary project: Hardware improvements of the UC2 Smartphone Microscope for schools (09/2020 - 01/2022)
01/2022	Practical Course, Medical Photonics program, FSU Jena	CourseBOX	Implementation of the toolbox in a standard course, continued 04 - 07/2022

TABLE 4.5: An overview of all planned and presented UC2 workshops and courses. Bold: Milestones, details below. Italic: Seminary projects (Seminarfacharbeit). Gray: Canceled to to the COVID-19 pandemic.

Summary of the milestone events and the key findings from them:**The Light Sheet Microscope Hackathon:**

- Thirty participants with the opportunity to build a light sheet microscope from the basic 3D-printed and external components.
- They could come up with new ideas for improving the toolbox in terms of CAD design and programming.
- The light sheet system of this workshop became one of the base systems for the FullBOX. See the Light Sheet Microscope in section 4.2.1.
- **Key findings:**
 - The entry level was still high.
 - It is more efficient to take the ideas for improvement from the informal feedback.

The FullBOX testing:

- Janelia Research Campus, USA, and NorMIC imaging facility, University of Oslo, Norway
- Structured in small groups working with one BOX each.
- Improvements for the latter workshop lied in the control of the electronics and in the preparation of the event structure and provided documentation.
- **Key findings:**
 - The 3D-printed modules not sufficiently robust, since after their use in the two events, some of the inserts started to break.

Trends In Microscopy Spring School (TiM):

- First time testing the hypothesis saying that the educational toolbox is so simple that anyone can use it to not only understand but more importantly to teach optics.
- Extended FullBOX used for the demonstration of the Incubator-enclosed Microscope, Smartphone Microscope, and Light Sheet Microscope, three spring school sessions.
- Given by Dr. Aurélie Jost from the Microverse Imaging Center and Prof. Rainer Heintzmann, who were trained beforehand.
- **Key findings:**
 - There is a multiplicative factor in the training, through which the impact of the toolbox can be expanded.
 - With manuals, training, and support the toolbox becomes an educational tool independent of its developers.

The MiniBOX testing in distance education:

- **Online workshops:**
- Participants borrowed the MiniBOXes beforehand. Introduction of the toolbox and guidelines for the experiments conducted via a video call.
- SFZ witelo e.V. spring holiday workshop (Fig. 4.19a)
 - Three participants of the age of 13 – 15 years, three-hour session.
 - Hands-on experience with a projector, telescopes and a microscope, preparing home-made microscope samples and observing them.
 - Given by Dr. Christina Walther of witelo e.V., with support for answering questions from my side.
- Microverse Imaging Center (Fig. 4.19b)
 - Twenty one participants, students and users of the imaging facility, two 15-minute sessions (an introduction and a break-out session for exploring).
- **Key findings:**
 - Better results when the participants can ask questions during the whole hands-on part and do the experiments with the tutor.
 - In an in-person workshop, it is easier to follow the instructions when the participants see the introduction live and work in groups.
- **Implementing MiniBOX in the Practical Course:**
- The “Plymouth Experiment” of the CourseBOX (section 4.1.4).
- During the period without any on-site teaching (summer 2021), we updated the experiment manual for the use of the MiniBOX.
- Students could do the experiments in the comfort of their home.
- Support from the supervisors, very positive feedback from the students (the first course in their master studies that was not purely online).
- **Key findings:**
 - The comprehension and results of the students were comparable or improved w.r.t. the standard course in the previous semesters.
- Four main suggestions for improvements:
 - Include a reliable white light source (expected, not possible due to safety reasons).
 - Include two diaphragms (expected, not manageable in the time frame).
 - The Z-stage causing confusion, the students did not comprehend the working principle even after watching the introductory video [83].
 - The alignment was rated as challenging or even difficult, but the results were satisfactory.

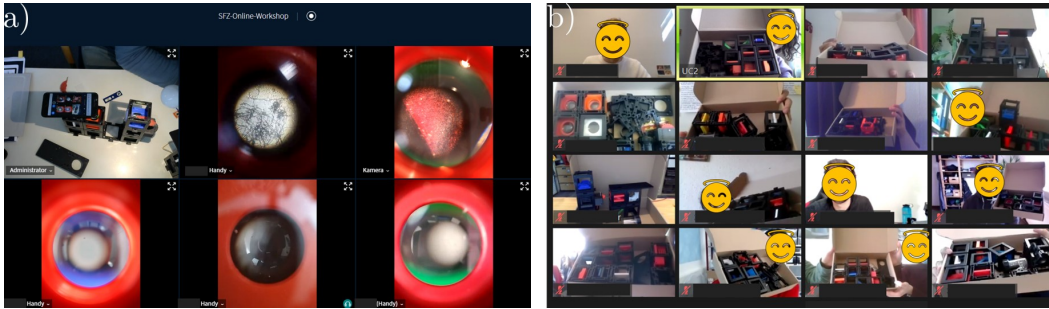


FIGURE 4.19: Screenshots from the distance education workshops. a) SFZ witelo e.V. holiday workshop. Participants were sharing the screens of their smartphones during the alignment of the Smartphone Microscope. b) Microverse Imaging Center microscopy course.

“Seminarfacharbeit” - seminar projects:

- We hosted four student groups (marked with dates in *italic* in Table 4.5).
- Each of them gave a valuable contribution to the UC2 project.
- Two of the projects are discussed in more detail in section 4.2.2, in the context of the Smartphone Microscope that they worked on.
- These results confirm the pedagogical value of the UC2 toolbox and show its direct implementation in the schools.

Additionally to all the mentioned events, we participated in the Frugal Science course (BioE271) of the Stanford University, which is a global project class, an example of MOOC, by giving a lecture on Optics with practical demonstrations using the UC2 toolbox (Lecture 11 available at [94]).

4.3.2 User input

In the development of the educational BOXes and microscopes we must acknowledge the contribution of the users, both those who came up with their own ideas and those who gave feedback on their experience after testing it. This is what ensures the validity of the presented results for their use. Rather than searching for an application of our system, we relied on the users telling us their needs and we developed the products accordingly. Many times we faced a demand for a tool and we were able to answer it in short time thanks to the modular system that is easy to adapt and upgrade.

Despite the low entry barrier for the end users, it still requires a great deal of time and effort to actively join such an open-hardware project and to design one’s own device or improve the existing systems. For this reason, most of the

design contributions come from either school projects or internship students, in both cases directly supervised by the UC2 core team members.

We supervised a number of Master students in the past years, many of whom gave an important contribution to the further development of the project. And all of them had the opportunity to learn and apply their knowledge fast in a straightforward way, without worries about breaking professional lab equipment. This is yet another example of the benefits of employing low-cost components in higher level education.

It is common for open-hardware projects in their first years that the number of active contributors from outside grows slowly. There are several research groups around the world who replicated some part of the toolbox and also those who work with the equipment provided from our side. There is a growing user base and interest in the project, therefore it is expectable that the point will come when more contributions come from the outside. Currently (18.03.2021), the UC2-GIT [7] has 281 stars, 41 watchers, and 52 forks, and there are 7 contributors not related to the research group (13 in total).

With increased accessibility of the basic toolbox, for example by providing ready-to-use kits or builder kits, the effort of adding their own module could be lowered for the users, since there will not be the need to build everything from scratch before getting into the use and development itself.

An example of a module developed by a user comes from the Institute for Zoology and Evolutionary Research at the FSU Jena, where they experimented with their own aquarium module, a 2×1 cube with glass covers on the sides. This module was used instead of the sample holder and living insects were observed under the microscope, while they moved on the glass bottom (Toni Wöhrl, electronic communication, 18th of November 2020).

The toolbox was also implemented by Haverkamp et al. at the WWU university in Münster (Westfälische Wilhelms-Universität) as a modular kit with various wave optics education experiments for explaining the basics of quantum technology. They upgraded the modules for their purposes and the result is a low-cost but reliable version of the Michelson interferometer, Mach-Zehnder interferometer, and three experiments regarding polarization [95].

It was also the user feedback that pushed the design criteria to their limits, demanding solutions that are reliable and accessible. To fulfill all the points defined in the decision matrix in section 2.4 and find a solution for the diverse applications, the toolbox exceeds other system in the level of its modularity. Therefore, the cubes-and-puzzles platform offers a universal tool and could be used in fields that were not yet considered.

Chapter 5

Conclusion

The previous chapters provide only a little insight into the versatile open-source UC2 toolbox and only in the educational context. The power of the system lies in its flexibility and the potential to easily adjust and implement different methods, tools, and ideas, and combine them with the work of others. Here the main outcomes of the educational branch development are summarized and the next steps are outlined.

The goal of this thesis was to develop the UC2 project further in the direction of the educational application. This included structuring and documenting it in order to lower the entry barrier and increase the accessibility for all the interested user groups. In terms of hardware development, the goal was to provide comprehensive educational kits.

5.1 Current state of development

The toolbox developed iteratively over time. It was optimized based on the feedback from the courses, workshops, and other testing with the end users. We tested uncountable new ideas, approaches, and methods. The history and progress of the development is documented in the GitHub repository and available to anyone, following the open-hardware practices. From the tested versions we chose the best solutions and implemented them as stable modules and applications that serve as the basis of the toolbox.

The following points summarize the outcomes of this work:

- An alternative way was developed for learning and teaching optics or microscopy, one that does not require extensive prior knowledge and exclusive equipment. Optics is an ideal field for tinkering and exploring, because the results can be directly seen. The interest in this topic can hopefully be transferred to other STEAM fields as well via interdisciplinary education.

- We brought down the entry level of this field and provided the necessary hardware, which is accessible for a broad audience.
- The hardware is adaptable for both the education and research, following the criteria from the decision matrix and accounting for the importance of different features for different applications.
- The toolbox remains open-source, such that anyone has the freedom to benefit from not only our results, but also our other findings and the experience of open hardware development.

In particular, the result presented here is a platform of comprehensive educational kits with low entry barrier that offers the developed hardware for public use by defined user groups.

- The MiniBOX, meant for secondary school and high school level and for STEAM outreach, was developed to the state of a prototype.
- The experience will be used to bring the other BOXes and the educational microscopes to the same state, to provide professional educational tools for the university level.
- The BOXes are supported by educational materials and the whole toolbox is well-documented for both its usage and reproduction.

5.2 User feedback evaluation

Through the testing and demonstrations we collected both formal and informal feedback from users on different education levels and with different demands from the toolbox. We see these three examples as successful proves of the innovative potential of the project:

- Without targeted advertising, there is lately a high demand for purchasing the BOXes and also the (science-grade) microscopes. We always met with curiosity and interest in the innovative solution. The users were also more or less enthusiastic about implementing the system in their own work, depending on their background and available time. They often indicated that they would be more interested in using it if there was the possibility to buy a pre-assembled or even a ready-to-use version.

- We did an online survey (see results in appendix E) to estimate the demand, which unfortunately told us more about the reach of your network than the interested users, since we could not reach many people outside academia with it. Nevertheless, the global survey conducted in May 2021 with a total of 75 participants showed the interest in the ready-to-use BOXes. We learned mainly about the needs of higher education institutions, universities, and research institutions, indicating a great interest in having one FullBOX or 2 – 5 CourseBOXes and also 2 – 5 MiniBOXes or SimpleBOXes. About 30 % of the answers showed the interest in having the toolbox privately for tinkering, which indicates that this is a non-negligible user group.
- A great success for the documentation and an indicator that the toolbox is indeed a useful tool for the microscopy community is the pre-print published by Zheng, et al. from the Department of Bioengineering of Imperial College London [96]. The group used the modular UC2 toolbox and built their system with it and we only learned about it from the published pre-print. This confirms the low entry barrier and reproducibility, and proper engagement of the system as an alternative to the standard solutions.

We majorly rely on informal feedback and personal communication with the users. The formal feedback was acquired via the mentioned survey and short questionnaires at the workshop in Oslo. We keep collecting the feedback and suggestions and using it to improve the toolbox.

5.3 Future perspective

These factors play an important role in considering the future progress of the project:

- Founding a company, producing the comprehensive BOXes and the modules to upgrade them, and making them available for sale. This is the next logical step based on the user, or potential customer feedback and our experience from the development and testing of the toolbox.
- Staying open-source and maintaining the high standard of the documentation, keeping it updated, and supporting the community formed around the project. This is important for the growing community of users interested in tinkering and reproducing the toolbox themselves.

They are mostly scientist or engineers and can contribute to the toolbox development. The educational applications can then benefit from their contributions.

- Scaling the production and certifying the products. In the education environment, there is a need to buy the ready-to-use solutions, rather than create them. It must be ensured that the equipment and the user manuals are coherent with the school syllabus and the interests of the out-of-school educational institutions. There is a demand for the toolbox as an educational tool on both pre-university and university level.
- Quantitative testing of stability, reproducibility, and materials. This is especially important for the scientific applications.
- The health and environmental risks has to be assessed. This includes for example light source safety, risk of swallowing small parts, risk of microplastics released from the PLA components.
- Furthermore, there is an apparent need of a rapid prototyping system for optics and microscopy. The UC2 toolbox could be an answer to that. Through the development of the modular system, we gained the know-how on building optical setups in a simplified way and this could be transferred and focused in any other application.

The open UC2 toolbox is an innovative and versatile tool that proved its usefulness in the fields of photonics and education. In the future, it should also be an accessible platform of interdisciplinary research and development of knowledge, and help to develop other tools and provide answers in the STEAM topics. The toolbox should be used for training the students who can later implement it in building their own optical designs, closing the gap between education and science.

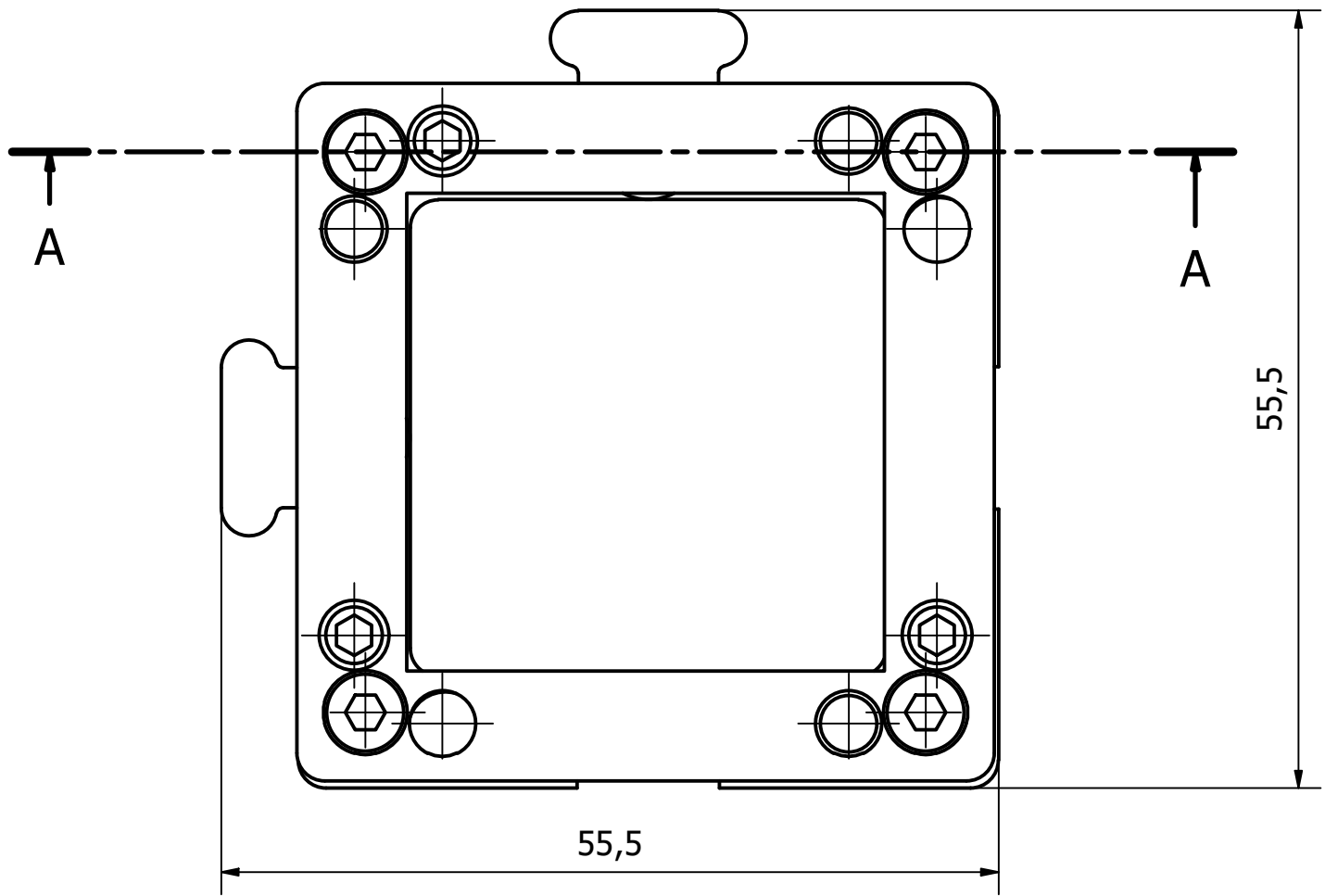
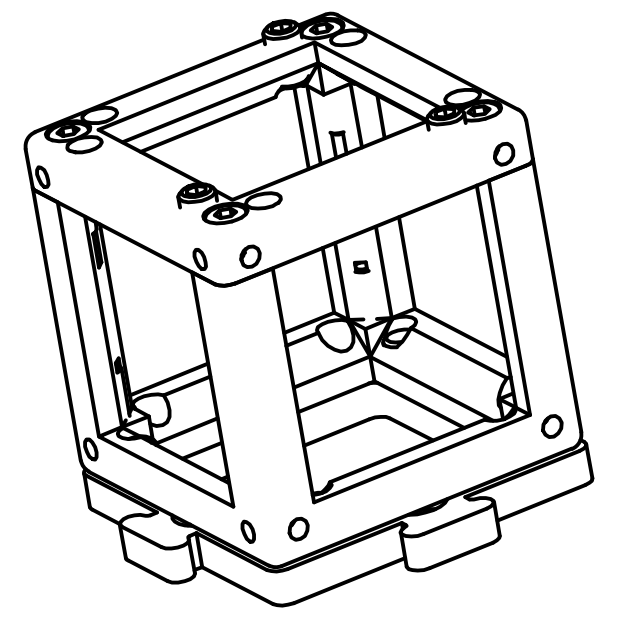
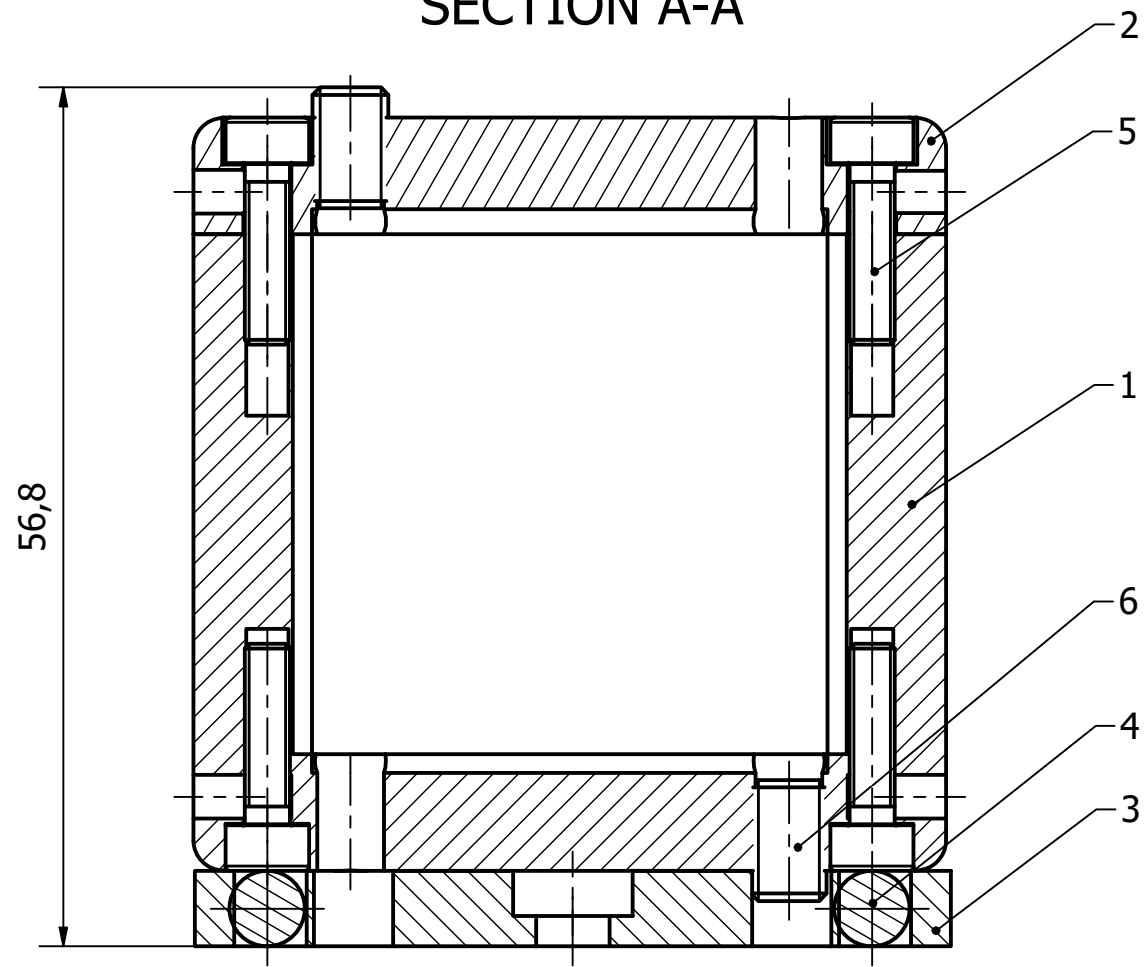
Appendix A


Technical drawings

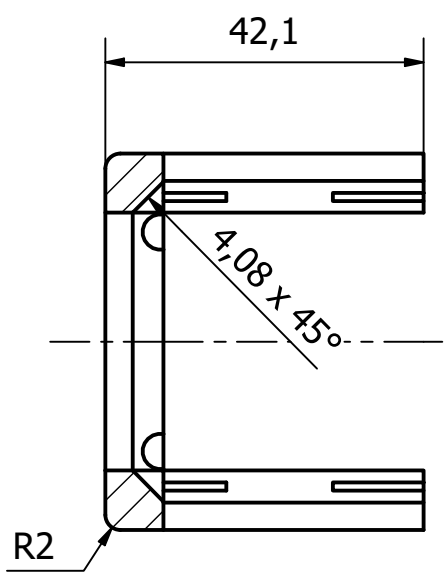
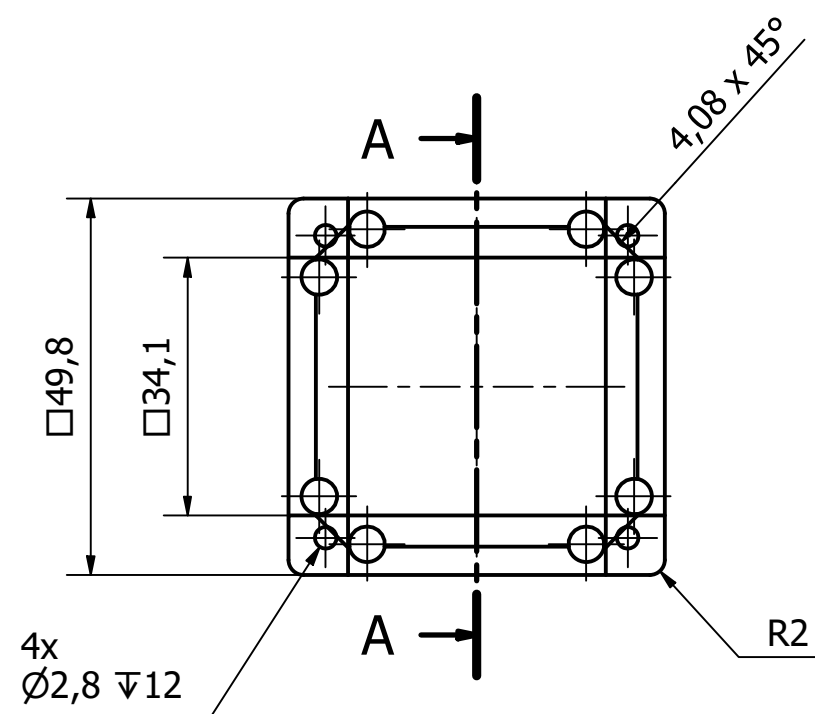
List of attached technical drawings:

1. **DWG01:** Assembly_Cube_empty_1x1_withBase_v3
2. **DWG02:** 10_Cube_1x1_v3
3. **DWG03:** 10_Lid_1x1_v3
4. **DWG04:** 10_Baseplate_puzzle_v3

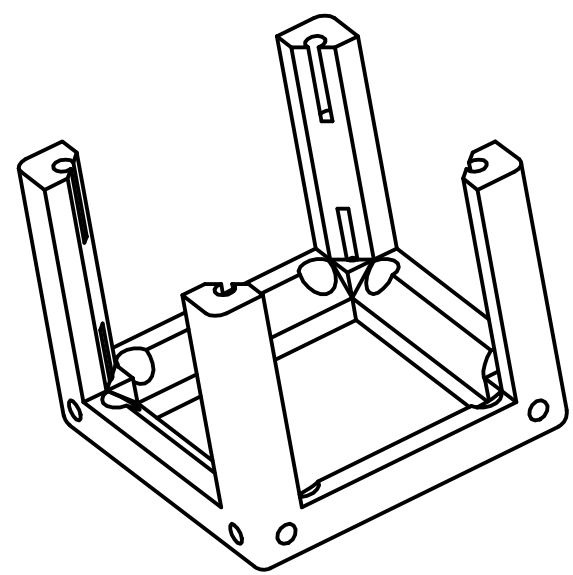
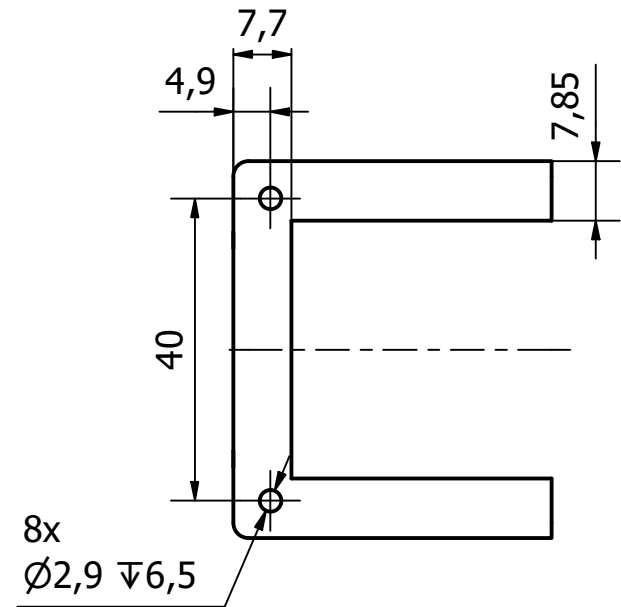
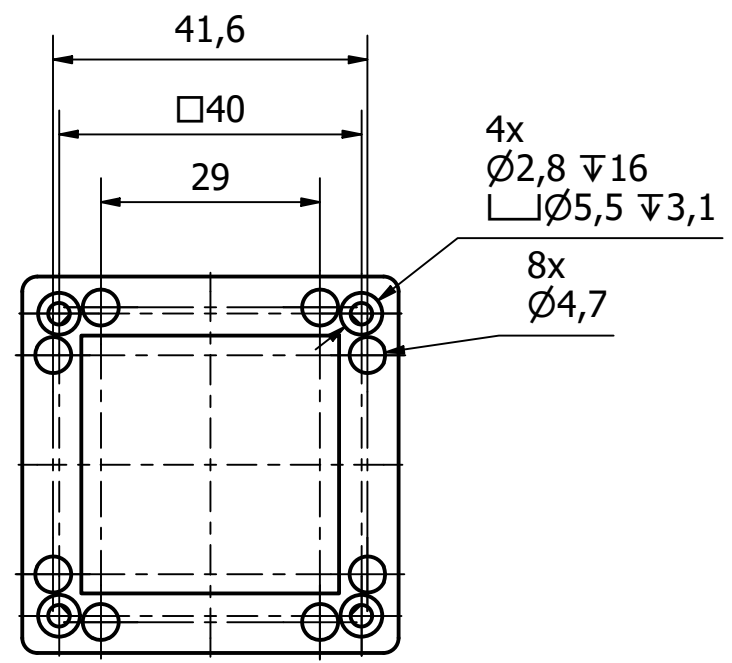
SECTION A-A




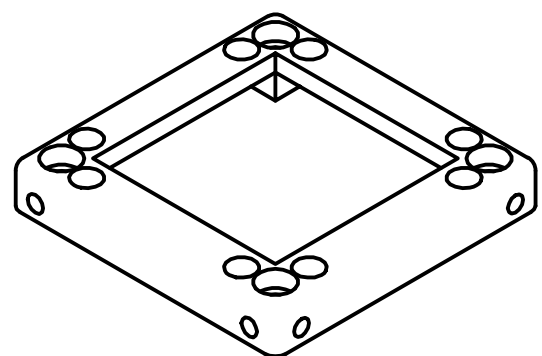
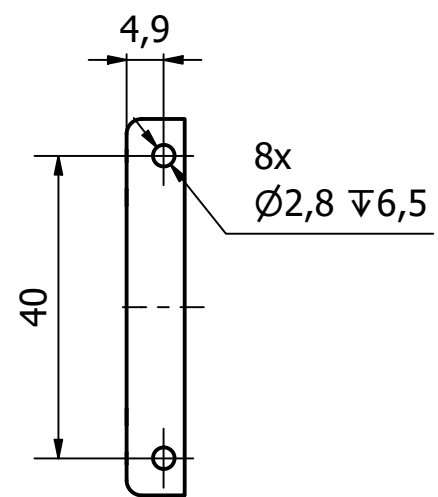
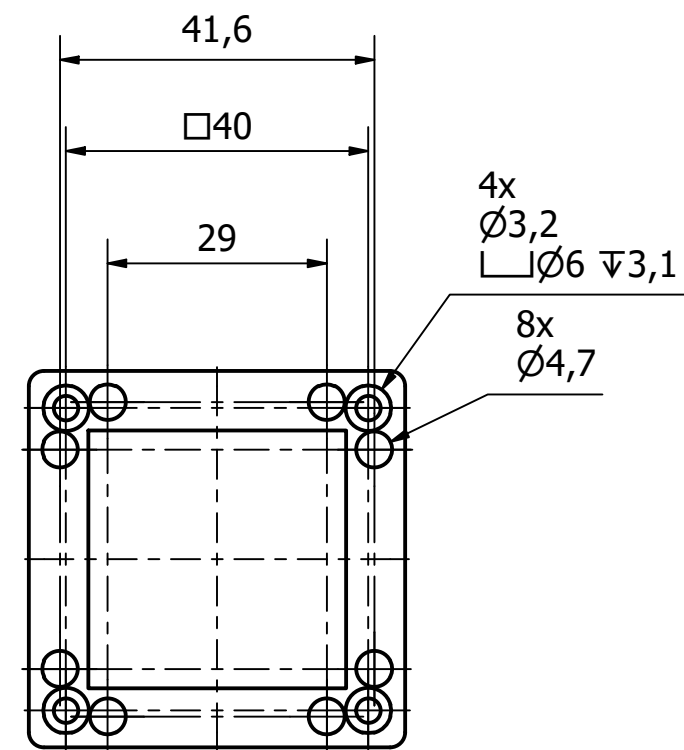
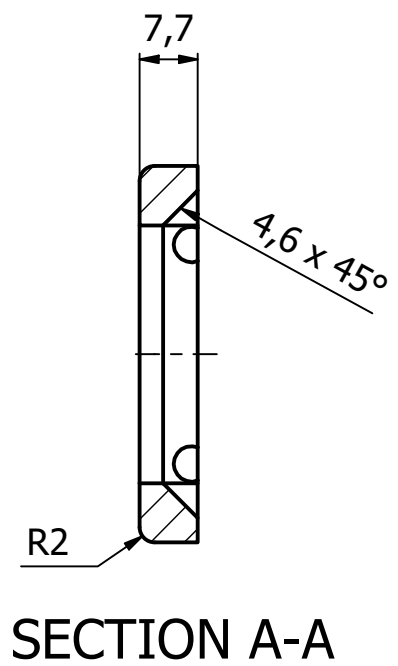
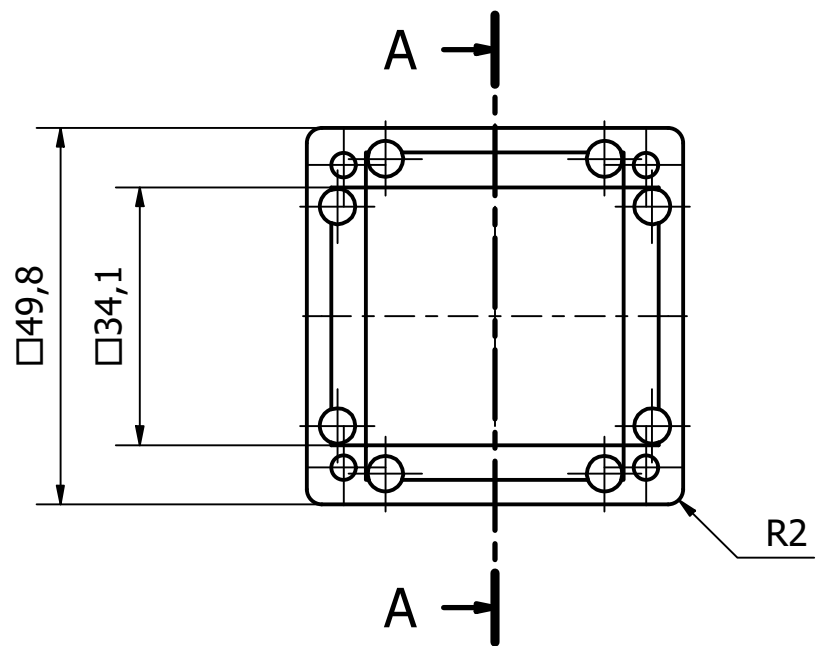
6	ISO 4026 - M5 x 8		6	Hexagon socket set screws with flat point
5	DIN 912 - M3 x 12		8	Cylinder Head Cap Screw
4	00_BallMagnets_5mm		4	
3	10_Base_puzzle_v3	DWG04	1	
2	10_Lid_1x1_v3	DWG03	1	
1	10_Cube_1x1_v3	DWG02	1	
ITEM	PART NUMBER	DWG	QTY	DESCRIPTION
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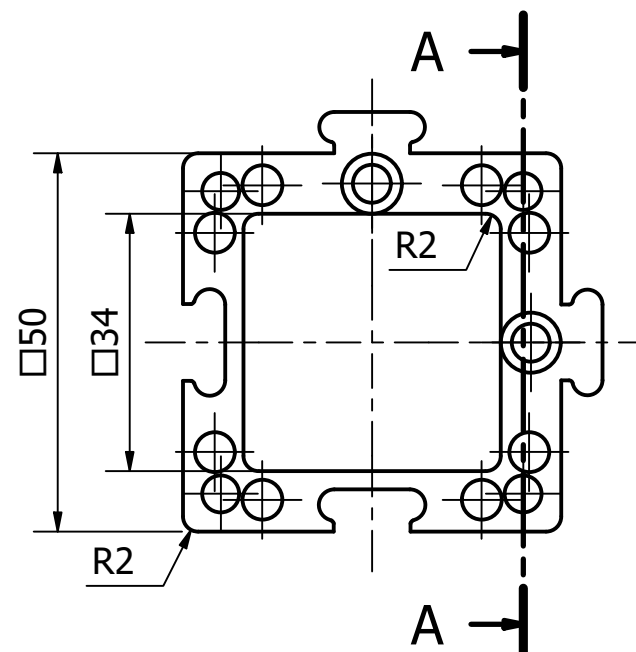
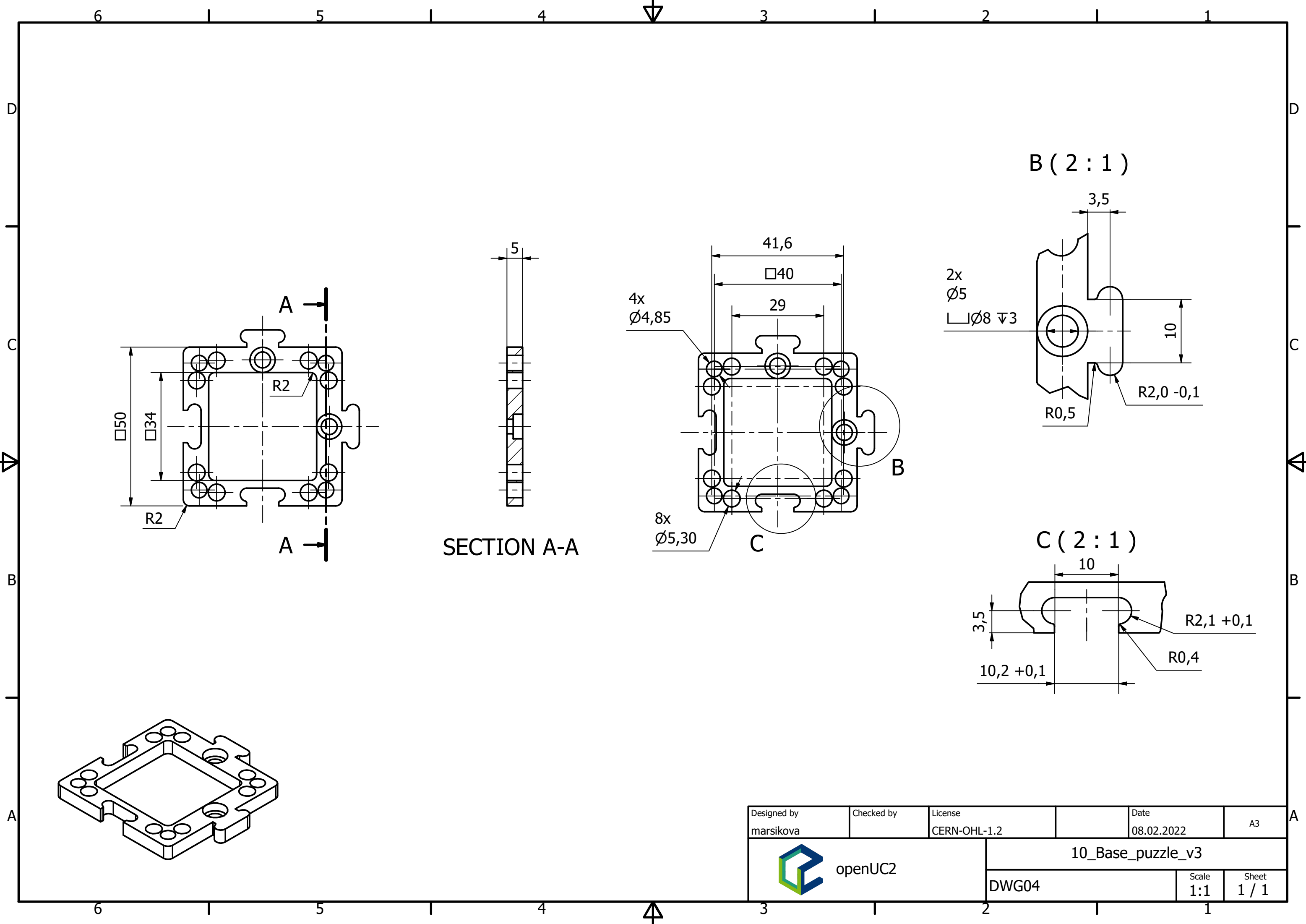
SECTION A-A



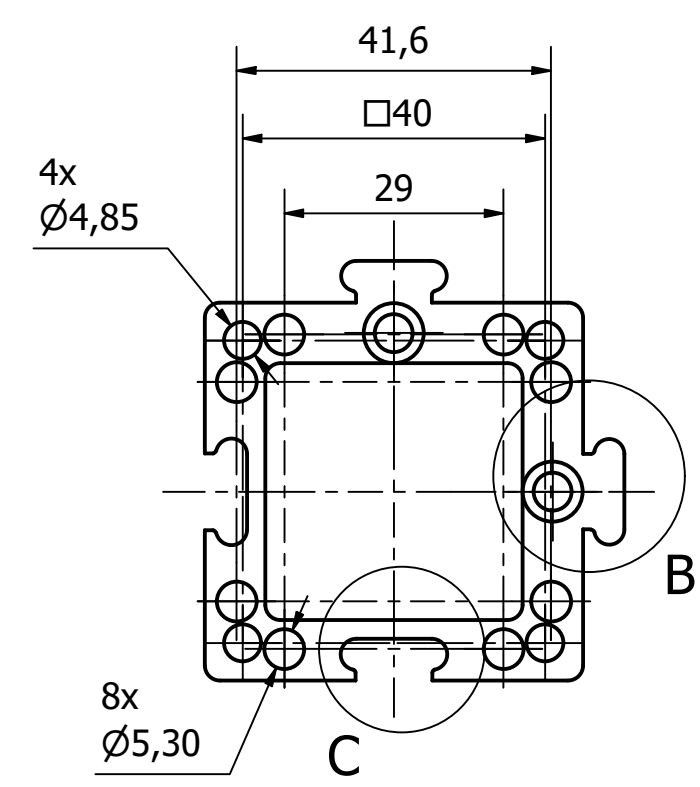
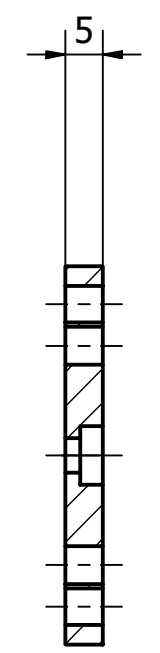
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		DWG02	Scale 1:1	Sheet 1 / 1



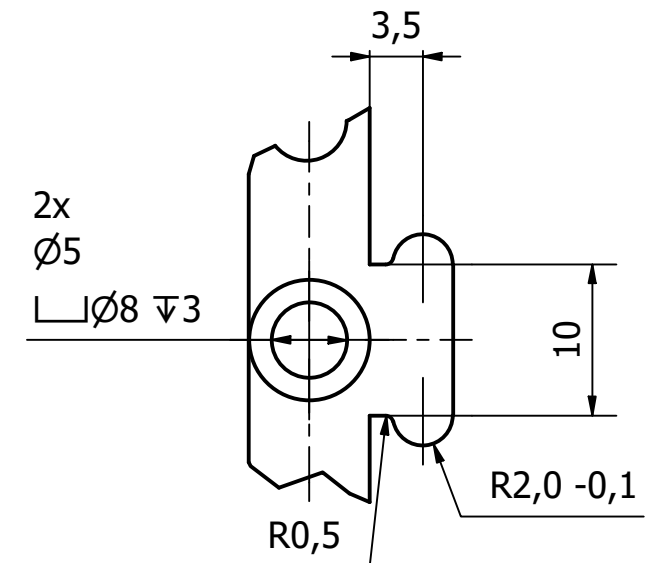
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		DWG03	Scale 1:1	Sheet 1 / 1



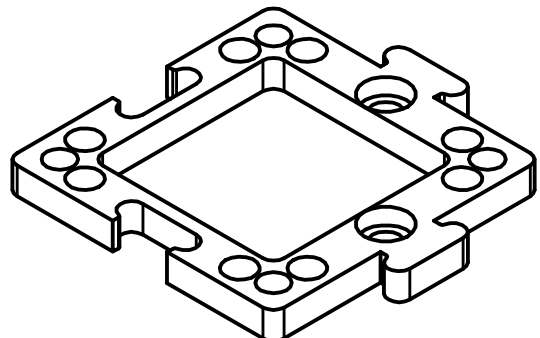
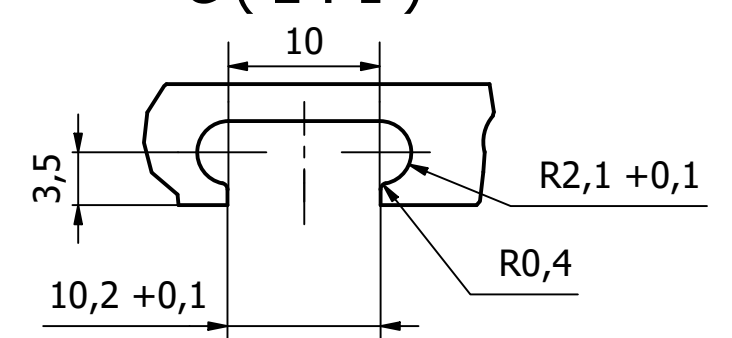
SECTION A-A




B (2 : 1)



C (2 : 1)



Designed by marsikova	Checked by	License CERN-OHL-1.2	Date 08.02.2022	A3
 openUC2		10_Base_puzzle_v3		
		DWG04	Scale 1:1	Sheet 1 / 1

Appendix B

MiniBOX booklet

The content of this booklet is based on the school syllabus and covers the ray optics experiment of 7th to 12th grade [82]. The didactical aspects were consulted with Dr. Christina Walther of the Schülerforschungszentrum witelo e.V. The graphical design was developed by Katrin Uhlig of the ÖA department of Leibniz-Institute of Photonic Technologies Jena e.V.



YOU. SEE. TOO.

MiniBOX

Leibniz | ipht 
LEIBNIZ-INSTITUT für
PHOTONISCHE TECHNOLOGIEN



YOU.SEE.TOO.



Das ist in der MiniBOX

Probenhalter

hält ein Objekt fest in einem Würfel

Spiegel

reflektiert das Licht

Linse

beeinflusst die Art und Weise, wie das Licht ausgebreitet wird

Mikroskopobjektiv

ein spezielles Linsensystem, welches ein Objekt vergrößert



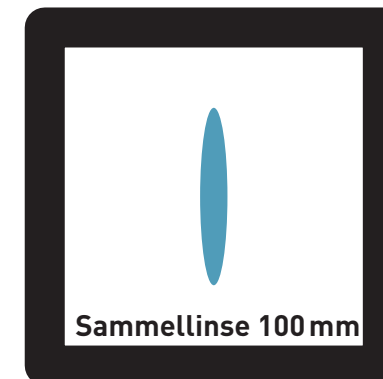
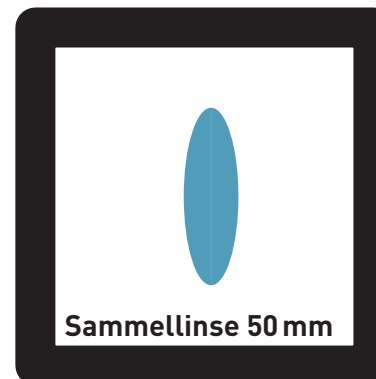
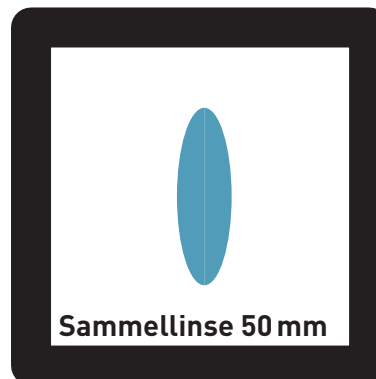
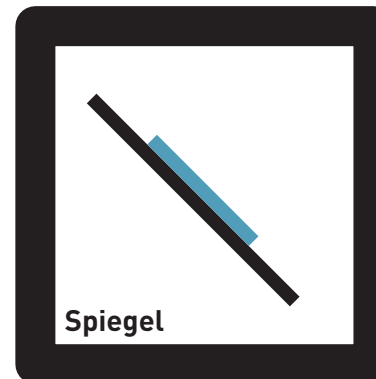
Vorsicht!

Berühre die Glasoberflächen nicht mit den Fingern!



Reinigung der Linsen

Wenn du die Linse berührt hast, kannst du sie mit einem Brillentuch reinigen.



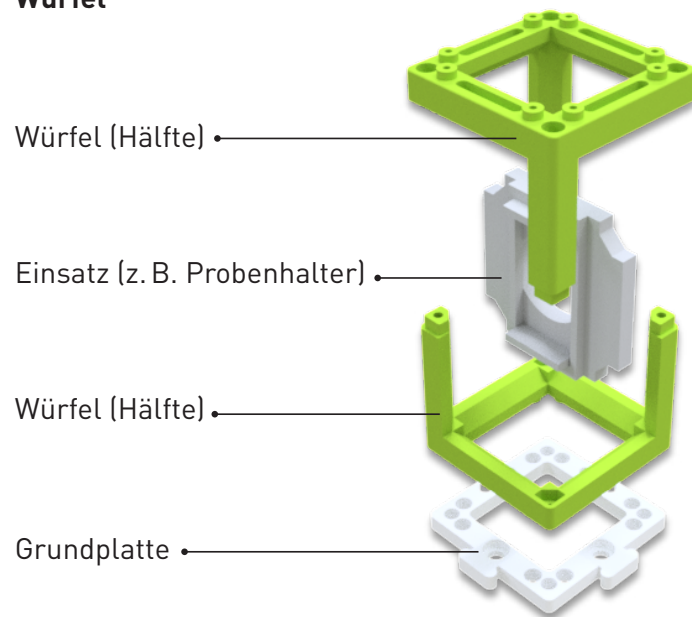
Das ist UC2

Das Kernelement des UC2-Projekts ist ein einfacher Würfel. Der Würfel besteht aus zwei Hälften und beherbergt einen verschiebbaren Einsatz. Der Einsatz kann verschiedene optische Komponenten (z.B. Linsen, Spiegel) halten, womit sich mit jedem Würfel unterschiedliche Funktionen realisieren lassen.

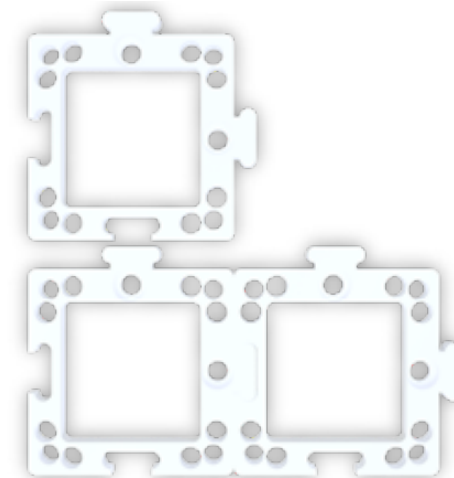
Würfeltyp 1

Spritzguss mit Steckverbindung

Würfel



Grundplatte



Der Würfel lässt sich auf eine Grundplatte montieren. Die Grundplattenmodule lassen sich wie Puzzle zusammenstecken.

Das ist UC2 zum Selberdrucken

Der UC2-Würfel lässt sich auch 3D-drucken. Er sieht genauso aus wie das Spritzgussmodell, besteht hier aber aus dem Würfel-Deckel und dem Würfel-Körper, welche mit Schrauben zusammengehalten werden. Die magnetischen Schrauben dienen dazu, sich mit den Kugelmagneten auf der Platte zu verbinden. Durch die Kombination verschiedener Würfelmodule lassen sich ganz einfach verschiedene optische Aufbauten zusammenbauen. Mit jedem Würfel kann eine neue Funktion hinzugefügt werden. Deiner Kreativität sind keine Grenzen gesetzt.

Würfeltyp 2

3D gedruckt mit Magnetverbindung

Würfel

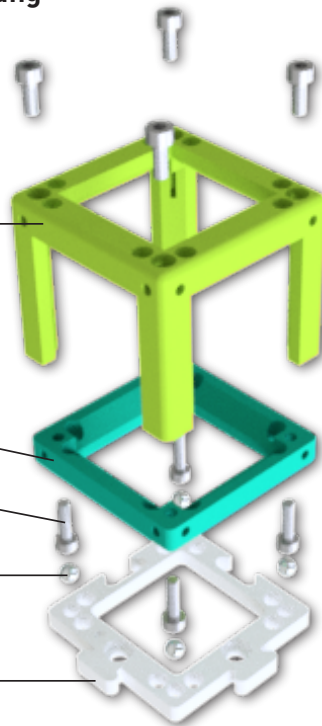
Würfel (Körper)

Würfel (Deckel)

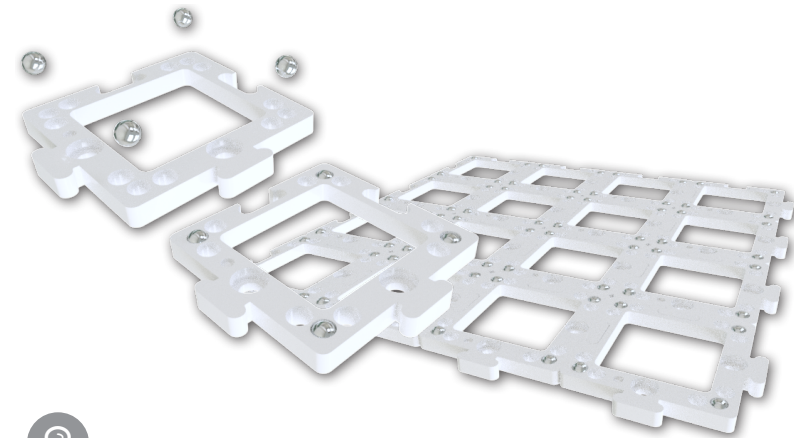
Schrauben (magnetisch)

Kugelmagnete

Grundplatte



Grundplatte mit Magneten

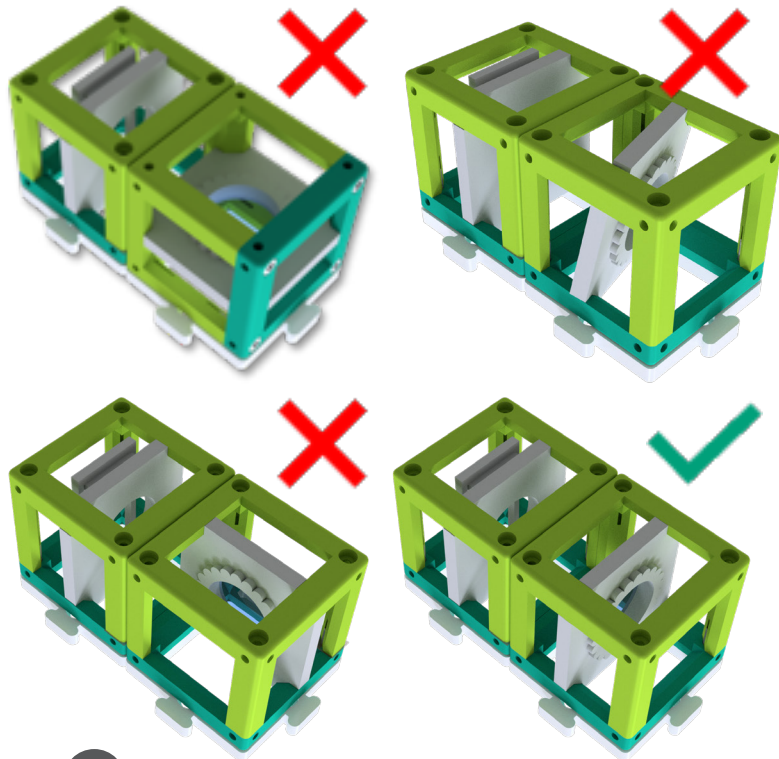


In der 3D-gedruckten Grundplatte sind kleine Kugelmagnete eingelassen, auf die die Würfel gesteckt werden.

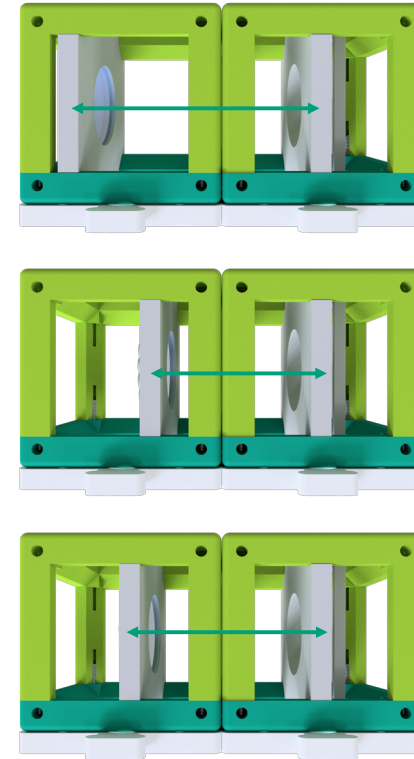
Willst du mehr Würfel haben? Dann kannst du sie selbst bauen. Du findest alles hier.



So passen die Würfel zusammen



Achte darauf, dass die Würfel richtig auf der Platte stecken und nicht verkippt sind. Am Ende ist es wichtig, dass die Einsätze an der richtigen Stelle sitzen.



Wenn du kein scharfes Bild siehst, verschiebe die Einsätze (z. B. Linse) so lange, bis du es klar siehst. Der grüne Pfeil im Bild zeigt dir, wie das geht.

Das kann eine Linse

Nimm einen oder mehrere der Würfel, in denen eine Linse steckt und schau dir das hier abgebildete UC2 Symbol da hindurch an. Halte den Würfel dabei in der Hand und verändere den Abstand zwischen der Linse und dem Bild.



?

Wie sieht das Bild aus?

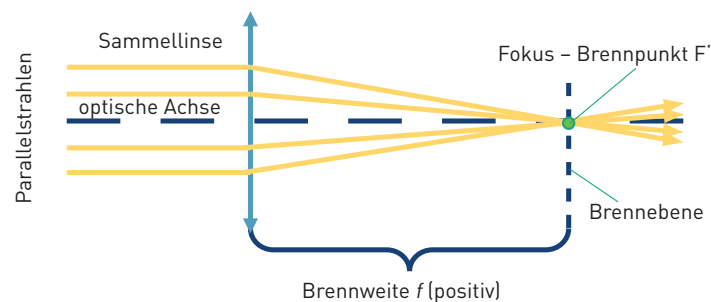
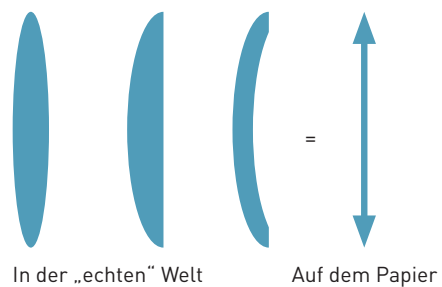
?

Verschiedene Linsen haben unterschiedliche Fähigkeiten. Welchen Unterschied beobachtest du zwischen den unterschiedlichen Linsen?

Linsen

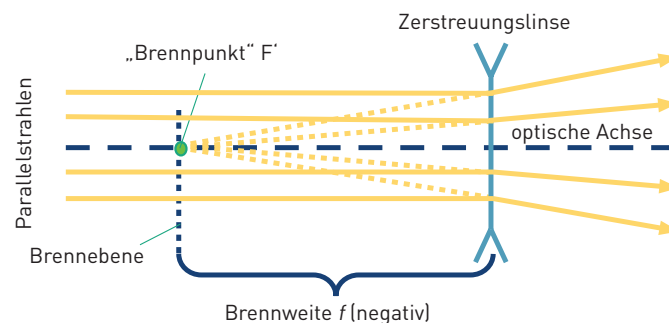
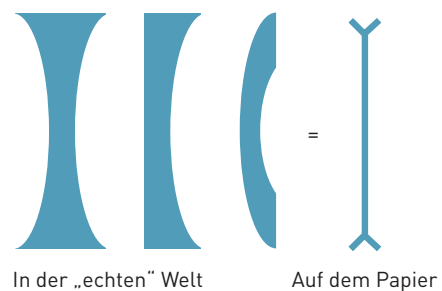
In der Strahlenoptik wird das Licht als Strahlenbündel (Pfeile) dargestellt, was eine Vereinfachung der physikalischen Eigenschaften von Licht mit sich bringt. Ein Strahl hat eine Richtung und wird daher mit einem Pfeil gezeichnet. Eine Linse „bricht“ den Strahl und ändert so seine Richtung.

Sammellinsen



Sammellinsen brechen die Lichtstrahlen, die parallel zur optischen Achse laufen, in einem Punkt, der **Brennpunkt** genannt wird.

Zerstreuungslinsen



Zerstreuungslinsen brechen die Lichtstrahlen, die parallel zur optischen Achse laufen als würden sie einem Punkt entspringen, der „**virtueller**“ **Brennpunkt** genannt wird.

Die **Brennweite** einer Linse entspricht hier der Distanz von der Linse zur Brennebene, auf der der Brennpunkt liegt. Sie wird in Millimeter angegeben ($f = \text{mm}$).

Linsen „brechen“ die Lichtstrahlen

Die Brennweite der Linse findest du als eine gedruckte Nummer auf den Linsenhaltern. Die MiniBOX enthält eine 100-mm-Sammellinse, zwei 50-mm-Sammellinsen und eine -50-mm-Zerstreuungslinse. Die Zahlen geben die Brennweite an.

Die Sammellinse heißt auch positive oder konvexe Linse. Der mittlere Teil der Linse ist immer dicker als der Rand.



Mit der Sammellinse kann das Bild vergrößert werden. Die Vergrößerung ist für die 50-mm-Linse und die 100-mm-Linse unterschiedlich. Das Bild kann aufrecht oder umgekehrt sein.

Die Zerstreuungslinse (Streulinse) heißt manchmal auch negative oder konkave Linse. Der mittlere Teil der Linse ist immer dünner als der Rand.



Mit der Zerstreuungslinse ($f = -50 \text{ mm}$) ist das Bild immer verkleinert und immer aufrecht.

Wir gehen davon aus, dass unsere Linsen so genannte „dünne Linsen“ sind. Das bedeutet, dass wir sie als eine Ebene betrachten können und uns nicht um ihre Dicke kümmern. Das macht Erklärungen und Berechnungen viel einfacher.



Haben die Antworten noch mehr Fragen aufgeworfen? Dann fahre fort, um herauszufinden, wie genau die Linsen funktionieren...

Linsen-Abbildung

Nimm jetzt die Linsen-Würfel zur Hand. Versuche, mit der passenden Linse die jeweilige Angabe über die Brennweite in den abgebildeten Würfeln zu entziffern. Bewege die Linse über der Schrift bis sie die gleiche Größe hat wie der Text „UC2“ in der Mitte.

?

Kannst du den Text in der gleichen Größe und Ausrichtung wie das „UC2“ sehen? Was passiert, wenn du den Abstand zwischen der Linse und dem Bild veränderst?

?

Was passiert, wenn du eine Linse mit der falschen Brennweite verwendest?

UC2

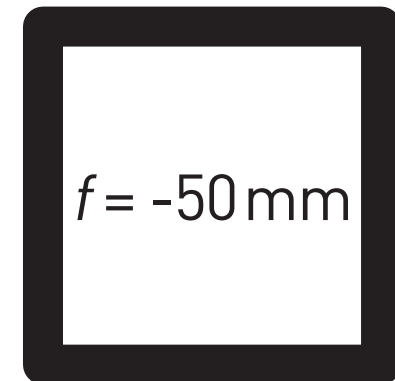
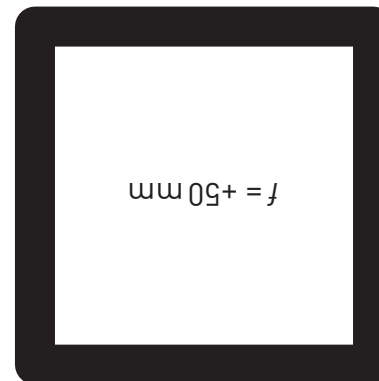
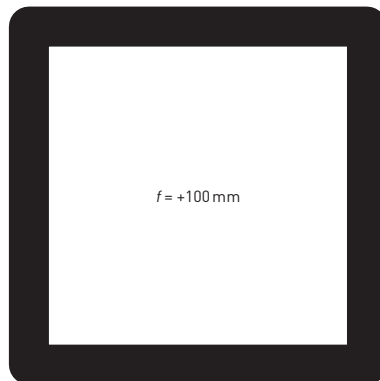


Abbildung eines Gegenstandes durch eine positive Linse

Als Beispiel nehmen wir die Sammellinse. Wir starten mit einem Gegenstand (grüner Pfeil) und schauen, was mit den Strahlen passiert, die von der Spitze aus starten. Es gibt unendlich viele Strahlen in alle Richtung, für das Zeichnen der Abbildung reichen uns aber die drei folgenden Strahlen:

1. Der **Mittelpunktstrahl** (orange) geht ungestört durch das Zentrum der Linse.
2. Der **Brennpunktstrahl** (gelb) startet auch von der Spitze des Pfeils, geht aber durch den objektseitigen Brennpunkt in der Brennweite f . Nach der Linse verläuft er auf gleicher Höhe weiter, aber nun parallel zur optischen Achse.
3. Der **Parallelstrahl** (rot) läuft zunächst parallel zur optischen Achse, wird dann aber an der Linse so gebrochen, dass er durch den bildseitigen Brennpunkt in der Brennweite f verläuft.

Das Bild entsteht dort, wo sich alle Strahlen schneiden. Das Prinzip ist für alle Punkte bzw. die davon ausgehenden Strahlen eines Objekts gleich. Je nach dem, welche Linse benutzt wird und je nach Position des Objekts, verändern sich die Eigenschaften des Bildes, die Größe, die Orientierung und die Position.

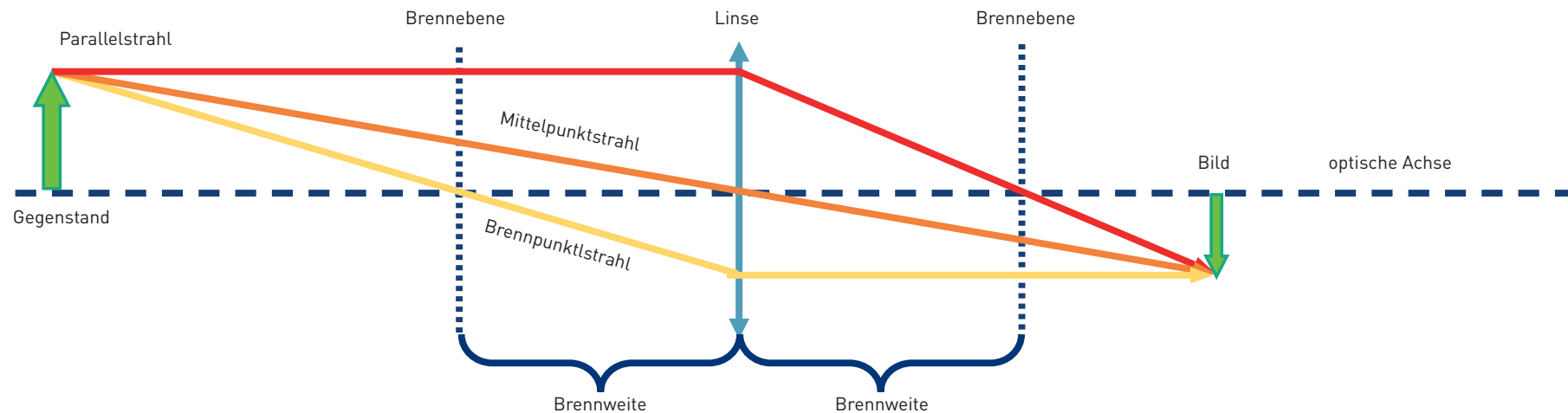
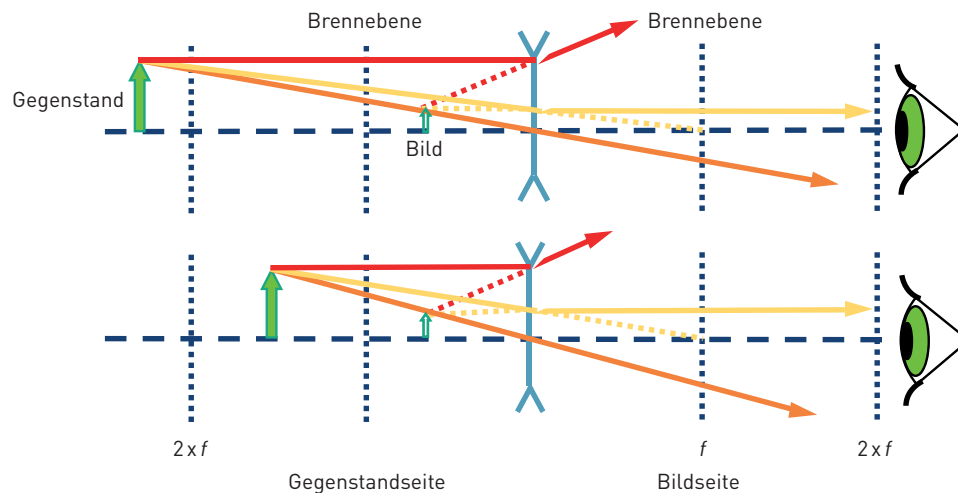


Abbildung eines Gegenstandes durch eine negative Linse

Im Fall der Zerstreuungslinse benutzen wir die gleiche Methode, um den Strahlengang abzubilden. Anders als im Fall der Sammellinse ist das Bild immer verkleinert und virtuell. Die Vergrößerung ist von der Position des Gegenstands vor der Linse abhängig. Anders als bei der Sammellinse entsteht das Bild auf der Objektseite und heißt damit **virtuelles Bild**. Du kannst es direkt mit deinen Augen sehen aber nicht auf einen Bildschirm projizieren.



Die Art und Weise, wie eine Linse ein Bild erzeugt, ist vorhersehbar, wenn man die Brennweite dieser Linse kennt. Deshalb muss ein bestimmter Abstand eingehalten werden, damit du die Schrift mit der angegebenen Linse auf dem vorhergehenden Blatt erkennst.



Mit der Zerstreuungslinse ($f = -50 \text{ mm}$) siehst du immer ein verkleinertes virtuelles Bild. Ein virtuelles Bild kann nur mit dem Auge betrachtet werden. Bisher haben wir nur virtuelle Bilder gesehen.



Die Vergrößerung und der Ort, an dem das Bild entsteht, hängen von der Brennweite der Linse und vom Abstand zwischen Linse und Objekt ab.

Die Sammellinse als Lupe

Nimm den UC2 Linsen-Würfel mit der Brennweite $f = 50 \text{ mm}$ und benutze ihn als eine Lupe.

Die Lupe ...

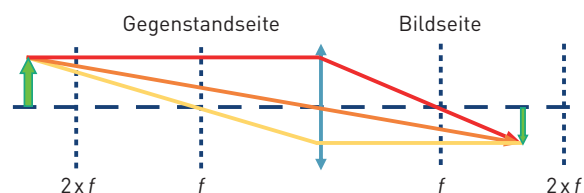


?

Kannst du durch die Sammellinse die kleinen Buchstaben lesen? Was steht dort geschrieben?

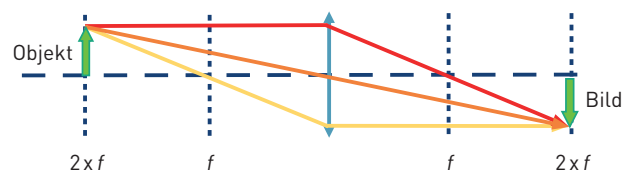
Das machen Sammellinsen

Von den Sammellinsen hängt die Vergrößerung und Position des Gegenstands ab.



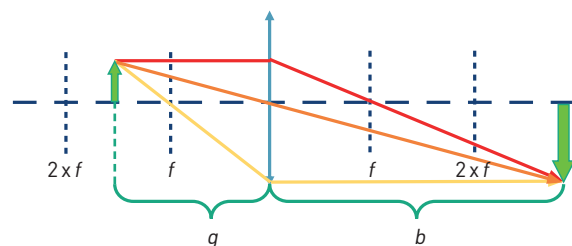
Wenn der Abstand zwischen Objekt und Linse mehr als dem doppelten der Brennweite der Linse entspricht, dann ist das Bild ...

- umgekehrt
- seitenvertauscht
- verkleinert
- reell



Wenn der Abstand zwischen Objekt und Linse genau der doppelten Brennweite der Linse entspricht, dann ist das Bild ...

- umgekehrt
- seitenvertauscht
- gleich groß
- reell



Wenn der Abstand zwischen Objekt und Linse mehr als die Brennweite und weniger als dem doppelten der Brennweite der Linse entspricht, dann ist das Bild ...

- umgekehrt
- seitenvertauscht
- vergrößert
- reell



Bildweite (b)

Der Abstand zwischen der Linsenebene und dem von der Linse erzeugten Bild wird als b bezeichnet.



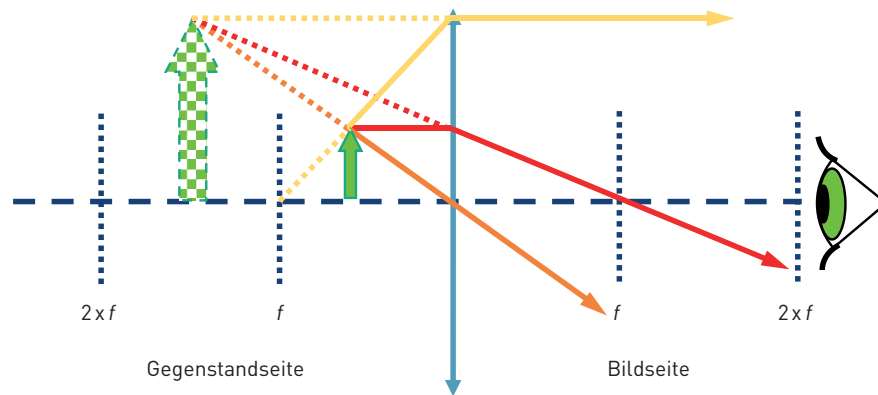
Gegenstandsweite (g)

Der Abstand zwischen dem Objekt und der Linsenebene wird als g bezeichnet.



Die Sammellinse kann ein reelles Bild erzeugen. Das reelle Bild sieht man dann auf einem Bildschirm.

Darum vergrößert die Lupe



Lupeneffekt

Wenn der Abstand zwischen Objekt und Linse weniger als der Brennweite der Linse entspricht, dann ist das Bild ...

- aufrecht
- seitenrichtig
- vergrößert
- virtuell



Berechne die Vergrößerung der Lupe mit der folgenden Formel:

$$V = \frac{250 \text{ mm}}{f}$$



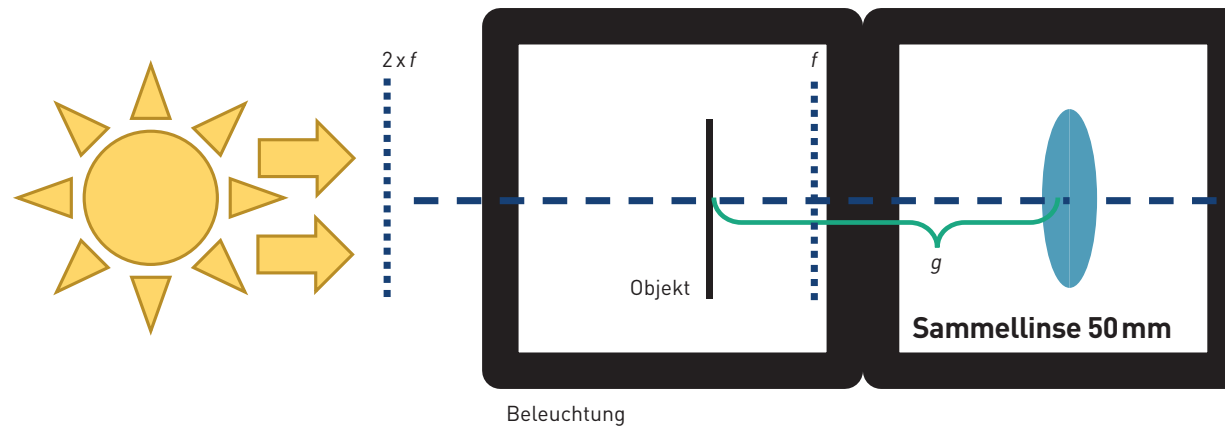
250 mm ist die Entfernung der deutlichen Sehweite – also der Abstand zwischen Objekt und Auge bei dem die meisten Menschen gut lesen können. Mehr dazu später in der „Akkommodation“ des Auges.



Die Lupe ist das einfachste aller optischen Geräte, denn es besteht bloß aus einer einfachen Sammellinse mit passender Brennweite. Warum vergrößert der Würfel mit der 50 mm den kleinen Text? Befindet sich das Objekt vor der Brennweite der Linse – also weniger als 50 mm vor der Linse – erzeugt die Linse ein virtuelles Bild, welches hinter dem eigentlichen Objekt liegt. Das Auge nimmt es vergrößert wahr. Schau dir dazu das Diagramm oben an.

So funktioniert ein Kinoprojektor

Nimm dir den UC2-Linsenwürfel mit der Brennweite $f = 50\text{ mm}$ und platziere ihn hinter den Probenhalterwürfel. Der Abstand zwischen dem Objekt und der Linse (also die Gegenstandsweite g) sollte ca. 60 mm entsprechen. Wenn du nun mit der Taschenlampe das Objekt beleuchtest, wirst du es in einem Abstand von ca. 300 mm auf der Wand scharf sehen. Ein Kinoprojektor hat statt des Objekts einen Filmstreifen und natürlich eine viel stärkere Lichtquelle.



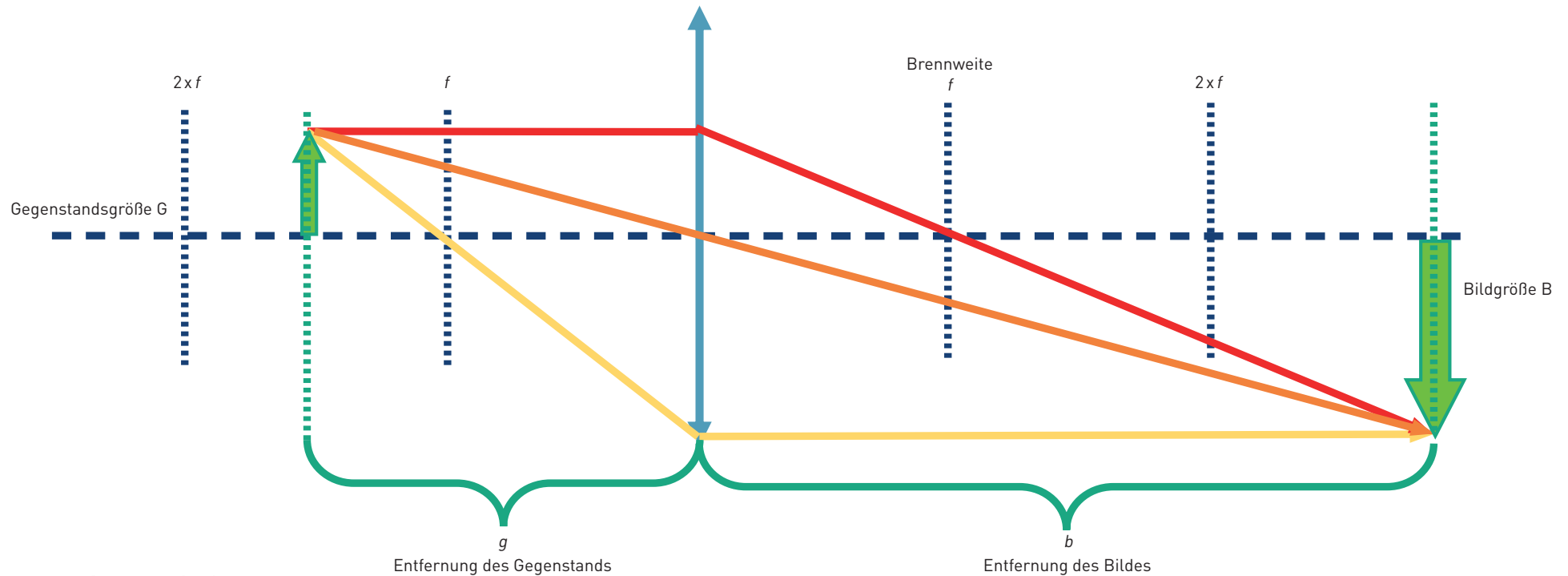
Benutze eine Taschenlampe (z. B. von deinem Handy) als Lichtquelle und halte es vor das Objekt.



Wie ist das Bild orientiert?

Schiebe die Linse in dem Würfel hin und her und beobachte, wann das Bild scharf ist. Finde das Bild für $g = 60\text{ mm}$, 65 mm , 70 mm und messe den Abstand zwischen der Linse und dem Bild.

So funktioniert der Projektor



Wo ist das Bild?

Bei der Abbildung eines Gegenstands durch eine Sammellinse hängen Lage und Größe des Bildes von der Entfernung (g) des Gegenstands zur Linse und von deren Brennweite (f) ab.

Die Linsengleichung beschreibt den Zusammenhang zwischen der Bildweite (b) und Objektweite (g): $\frac{1}{f} = \frac{1}{g} + \frac{1}{b}$

Wie groß ist das Bild?

Die Vergrößerung des Objekts auf dem Schirm lässt sich einfach mit der folgenden Formel ausrechnen: $V = \frac{b}{g} = \frac{B}{G}$

So funktioniert der Projektor



Prüfe, ob deine Beobachtung mit der Berechnung übereinstimmt.

$$\frac{1}{f} = \frac{1}{g} + \frac{1}{b}$$



Berechne die Vergrößerung des Projektors für die verschiedenen Werte g und b .

$$V = \frac{b}{g} = \frac{B}{G}$$

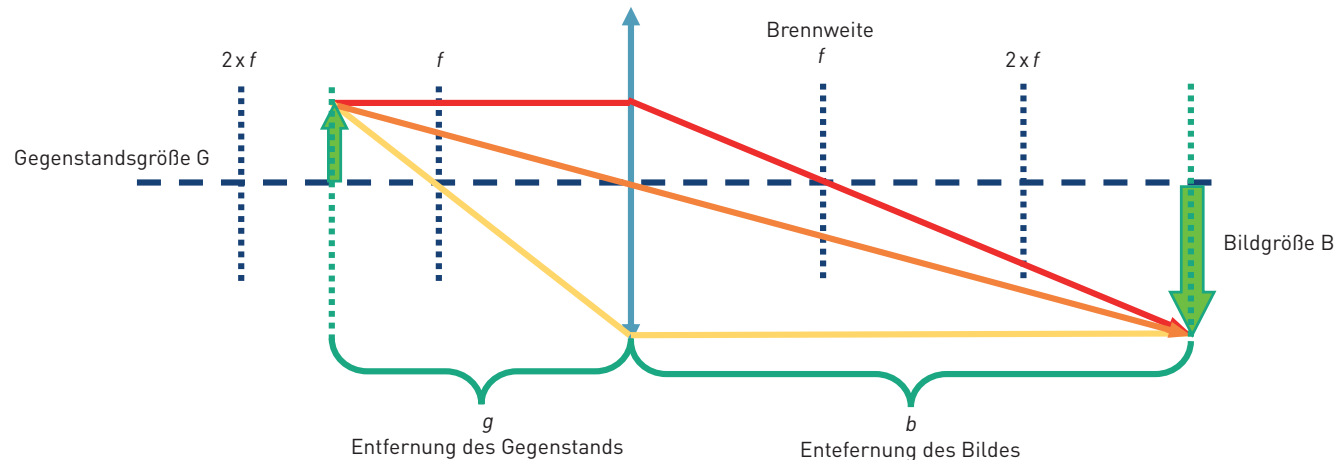


Unsere Linse hat eine Brennweite von $f = 50$ mm.

für $g = 60$ mm $\rightarrow b = 300$ mm

für $g = 65$ mm $\rightarrow b = 217$ mm

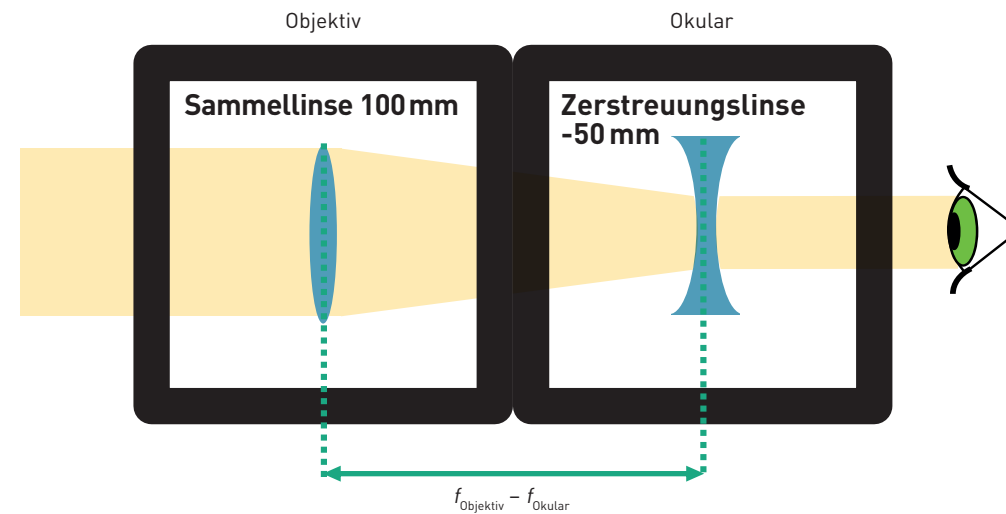
für $g = 70$ mm $\rightarrow b = 175$ mm



Der Projektor erzeugt immer ein vergrößertes, invertiertes (umgekehrtes) Bild. Die Position des Bildes und seine Vergrößerung hängen von der Position und der Größe des Objekts ab.

Das ist ein Galilei-Fernrohr

Stell die Linsen-Würfel auf das Blatt, wie in dem Diagramm gezeigt und schaue dann durch das Fernrohr in die Ferne.



?

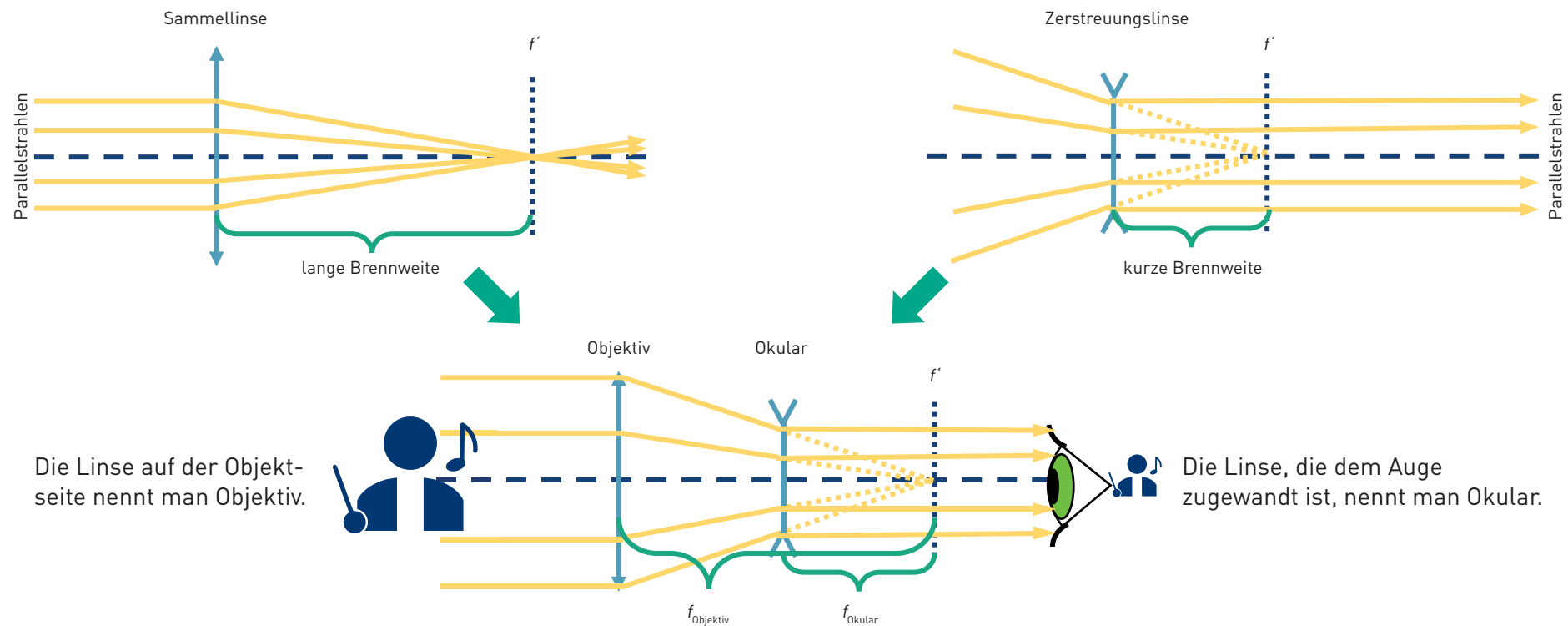
Wie sieht das Bild aus?
Wie ist das Bild orientiert?



Während du durch das Fernrohr schaust, passe die Abstände zwischen den Komponenten an, um ein scharfes Bild zu sehen!

So funktioniert das Galilei-Fernrohr

Ein Fernrohr ist ein optisches Instrument, das entfernte Objekte um ein Vielfaches näher oder größer erscheinen lässt.



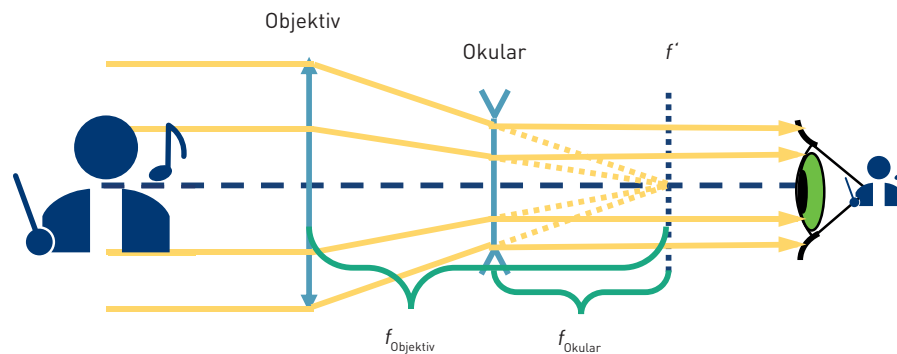
Die Linse auf der Objektseite nennt man Objektiv.

Die Linse, die dem Auge zugewandt ist, nennt man Okular.



Das Galilei-Fernrohr wird auch in Operngläsern verwendet.

So funktioniert das Galilei-Fernrohr



Wie lautet die Vergrößerung dieses Galilei-Fernrohrs?
Formel zur Berechnung der Vergrößerung

$$V = \frac{f_{\text{Objektiv}}}{f_{\text{Okular}}}$$

Sichtfeld bezeichnet den Bereich im Bildwinkel einer optischen Einrichtung, innerhalb dessen Objekte aufgezeichnet werden können.

Mit diesem Fernrohr kann man keine sehr hohe Vergrößerung erreichen. Dafür ist es sehr kompakt.



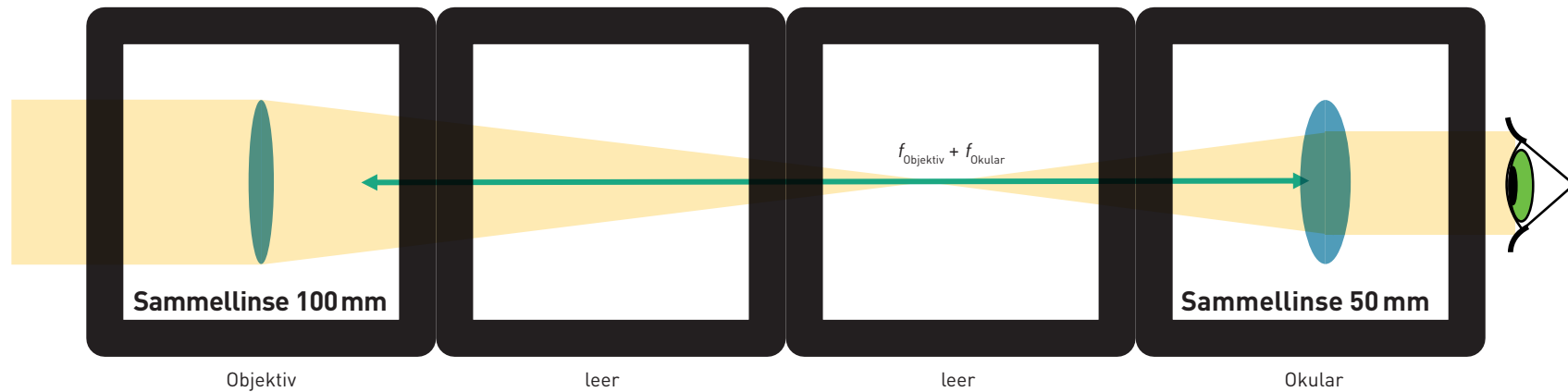
Das Bild ist immer

- vergrößert mit der Vergrößerung aus obiger Formel
- aufrecht
- seitenrichtig

Das Sichtfeld ist klein.

Das ist ein Kepler-Fernrohr

Stell die Linsen in die richtige Position, wie in dem Diagramm gezeigt. Dann schaue durch das Fernrohr in die Ferne.

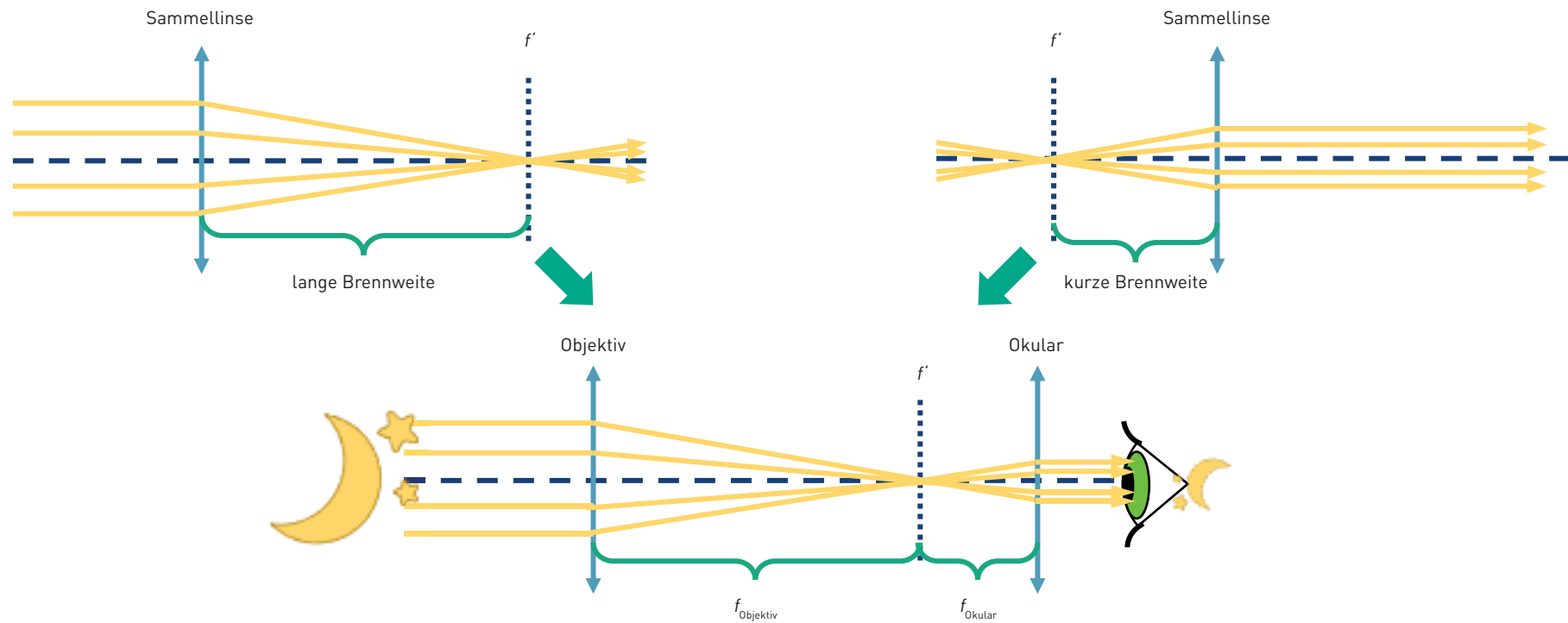


Wie sieht das Bild aus?
Wie ist das Bild orientiert?



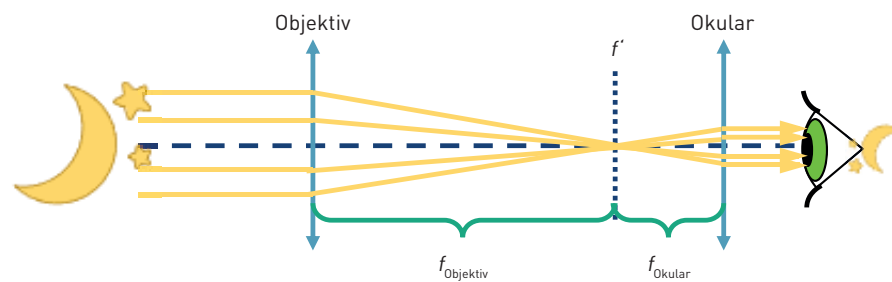
Während du durch das Fernrohr schaust, passe die Abstände zwischen den Komponenten an, um ein scharfes Bild zu sehen!

So funktioniert das Kepler-Fernrohr



Diese Art von Fernrohr wird häufig in der Astronomie benutzt.

So funktioniert das Kepler-Fernrohr



Was ist die Vergrößerung dieses Kepler-Fernrohrs?
Formel zur Berechnung der Vergrößerung

$$V = \frac{f_{\text{Objektiv}}}{f_{\text{Okular}}}$$



Dieses Teleskop kann eine höhere Vergrößerung als das Galilei-Fernrohr erreichen. Es erzeugt aber ein umgekehrtes Bild. Für die Beobachtung der Sterne ist das aber kein Problem.

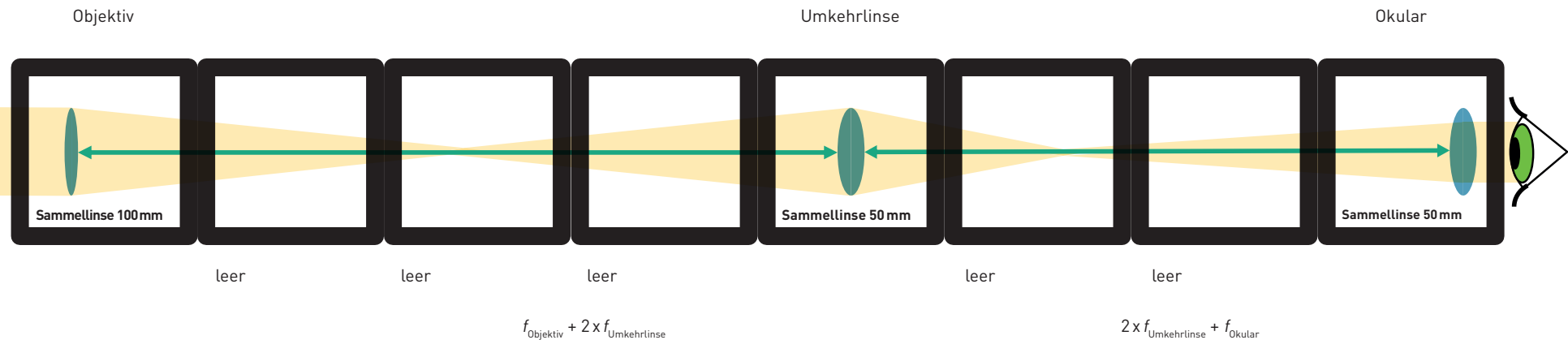
Das Bild ist immer

- vergrößert mit der Vergrößerung aus obiger Formel
- umgekehrt
- seitenvertauscht

Das Sichtfeld ist größer als beim Galilei-Fernrohr.

Das ist ein Beobachtungsfernrohr

Das Beobachtungsfernrohr ist lang, deshalb ist das Schema hier nicht so groß wie in der Realität. Stell' die Linsen in die richtige Position wie hier dargestellt und schau durch das Fernrohr in die Ferne.



?

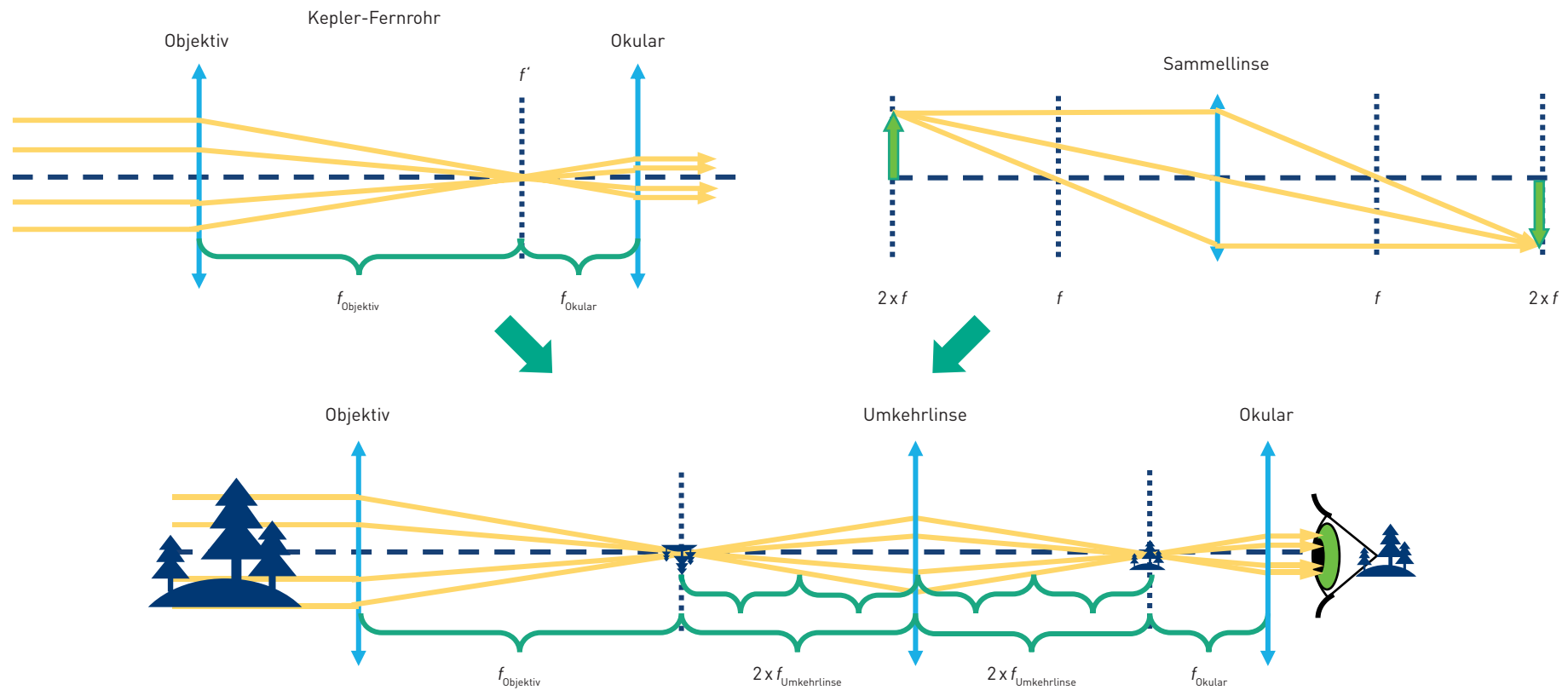
Wie sieht das Bild hier im Vergleich zum Kepler-Fernrohr aus?

💡

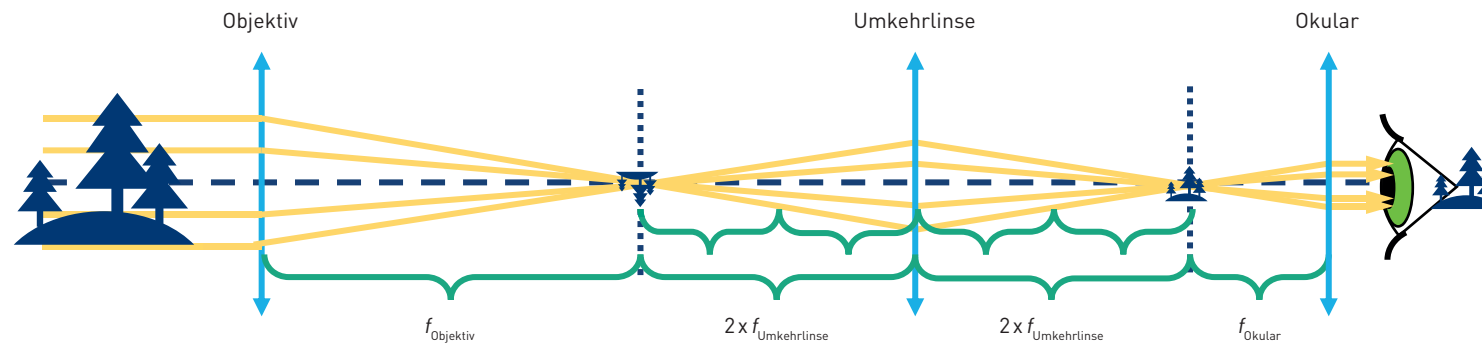
Während du durch das Fernrohr schaust, passe die Abstände zwischen den Komponenten an, um ein scharfes Bild zu sehen!

So funktioniert das Beobachtungsfernrohr

Das ist das einfachste Beobachtungsfernrohr. Das Bild ist umgekehrt im Vergleich zum Kepler-Fernrohr, weil das besser für die Beobachtung auf der Erde (terrestrisch) ist. Wenn du das Konzept des Kepler-Fernrohrs und das der Sammellinsenabbildung verstanden hast, kannst du sie einfach kombinieren wie hier gezeigt:



So funktioniert das Beobachtungsfernrohr



?

Die Vergrößerung ist so wie die des Kepler-Fernrohrs. Die Umkehrlinse verändert nur die Orientierung (das Bild wird umgekehrt), nicht die Vergrößerung.

Vergrößerung

$$V = \frac{f_{\text{Objektiv}}}{f_{\text{Okular}}}$$

Für terrestrische Beobachtungen ist ein aufrechtes Bild notwendig. Echte terrestrische Teleskope verwenden Prismensysteme, um das Bild zu drehen und kompakt zu halten.

Das Bild ist

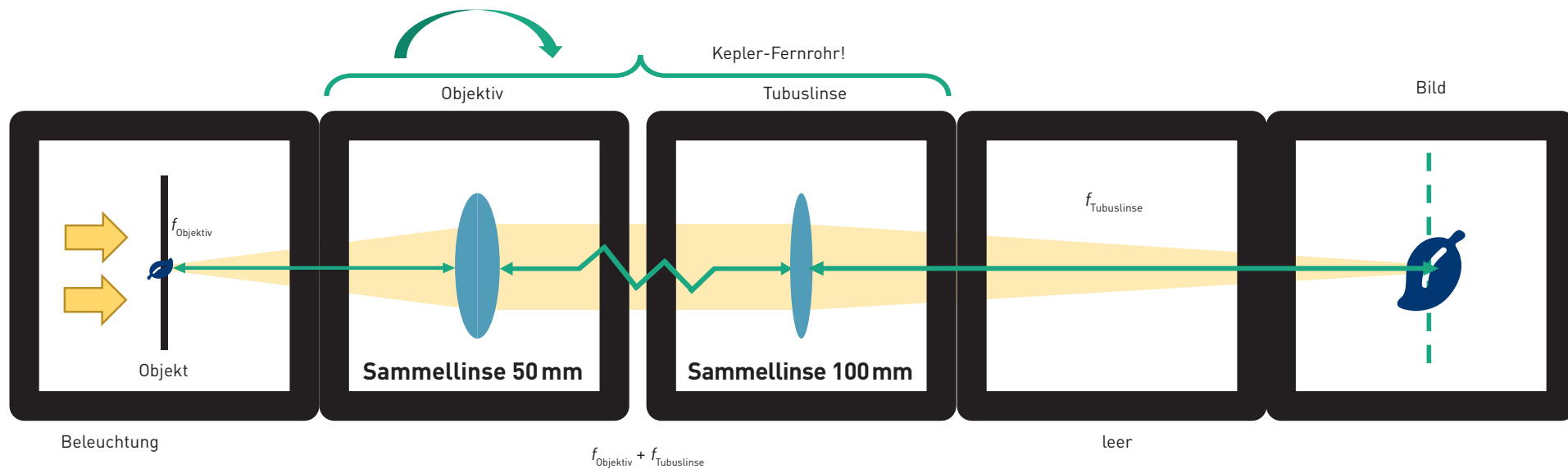
- vergrößert mit der gleichen Vergrößerung wie mit dem Kepler Fernrohr
- aufrecht
- seitenrichtig

Lichtmikroskop mit „Unendlich-Optik“

Stell das Objekt ca. 50 mm vor das Objektiv und finde das Bild ca. 100 mm hinter der Tubuslinse (mit einem Papier oder der Wand als Bildschirm), wie im Diagramm gezeigt. Bewege die Linsen so, dass du ein scharfes Bild erhältst.

?

Was passiert, wenn man das Kepler-Fernrohr umdreht?

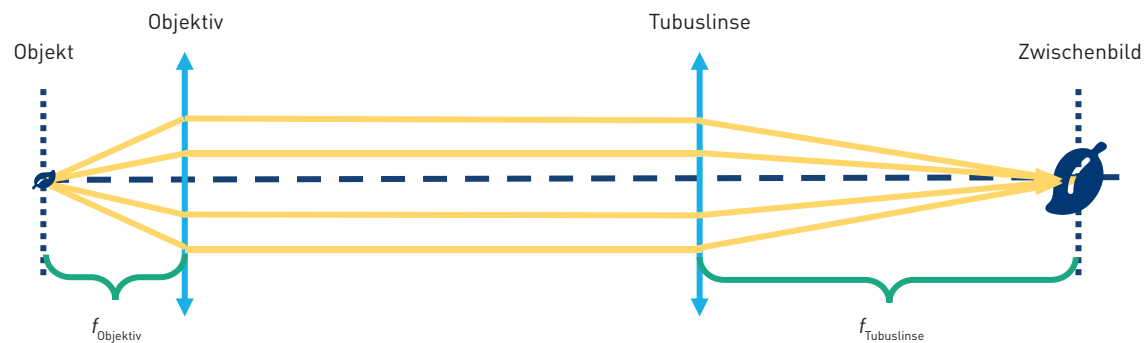


?

Platziere das Objekt mit dem Objektiv zusammen als eine Einheit auf dem Papier. Stell die Tubuslinse in einem Abstand von 100 mm zu deinem Bildschirm auf. Ändere die Entfernung zwischen den Linsen – ändert sich das Bild?

Das bedeutet „Unendlich-Optik“

Ein Mikroskop ist ein Gerät, das es erlaubt, Objekte stark vergrößert anzusehen oder bildlich darzustellen.



Das Bild wird **Zwischenbild** genannt, da es häufig noch mit einem Okular weiter vergrößert wird.



Das Objekt steht ungefähr in der objektseitigen Brennebene des Objektivs. Somit werden alle einfallenden Strahlen in ein paralleles Strahlenbündel hinter dem Objektiv umgewandelt. Das Objektiv hat eine kurze Brennweite.



Die Tubulinse erzeugt ein reelles Bild indem sie parallele Strahlen, die auf die Tubulinse treffen, in ihrer Brennebene sammelt. Wenn wir sie hinter dem Objektiv platzieren, wird das Objekt aus der Brennebene des Objektivs abgebildet. Die Tubulinse hat eine längere Brennweite als das Objektiv.



Das Bild in der Ebene des Zwischenbildes ist umgekehrt, seitenvertauscht, vergrößert und reell. Das reelle Bild kann man auf einem Bildschirm sehen.

Das bedeutet „Unendlich-Optik“

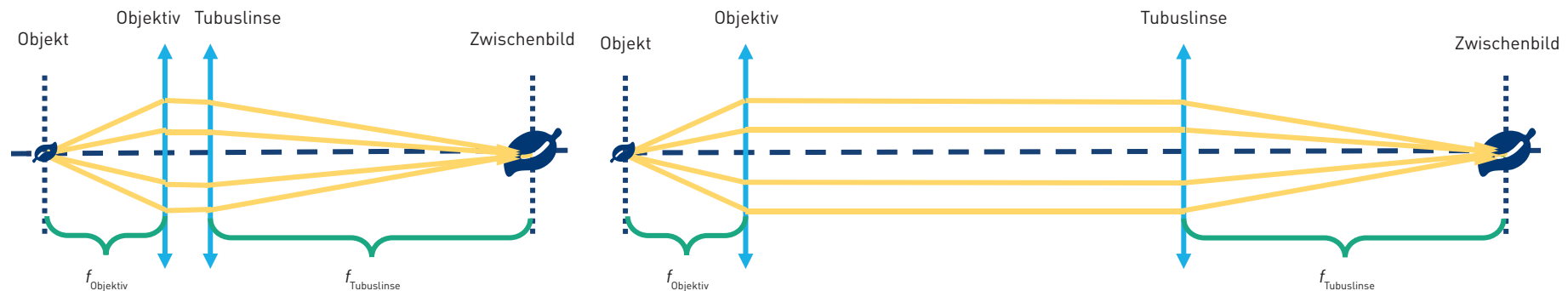
Ein Mikroskop ist ein Gerät, das es erlaubt, Objekte stark vergrößert anzusehen oder bildlich darzustellen.



Was ist die Vergrößerung des Bildes?



Vergrößerung $V = \frac{f_{\text{Tubuslinse}}}{f_{\text{Objektiv}}}$



Die Linsen des Kepler-Fernrohrs können auch für ein Mikroskop verwendet werden, aber in einer anderen Reihenfolge. Solange das Objekt in der Brennebene des Objektivs und der Bildschirm in der Brennebene der Tubuslinse ist, ist die Entfernung zwischen Objektiv und Tubuslinse egal, weil die Lichtstrahlen parallel sind.

„Unendlich-Optik“-Mikroskop mit Okular



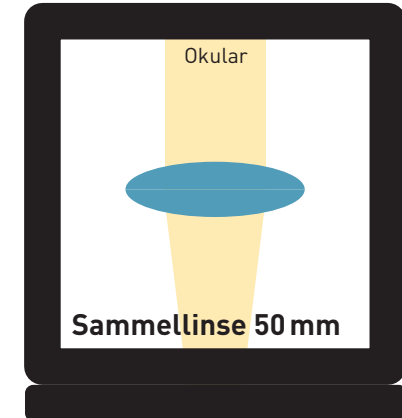
Der Aufbau unten zeigt ein ganzes Mikroskop. Stelle die Würfel auf die Positionen, wie im Diagramm gezeigt. Das Zwischenbild wird hinter dem Spiegel durch ein Okular abgebildet. Was siehst du wenn du hindurchschaust?



Bau' das Mikroskop wie ein Sandwich, indem du eine zweite Schicht mittels Grundplatte hinzufügst. Schau' von oben durch das Okular.



Während du durch das Mikroskop schaust, passe die Abstände zwischen den Komponenten an, um ein scharfes Bild zu erhalten!

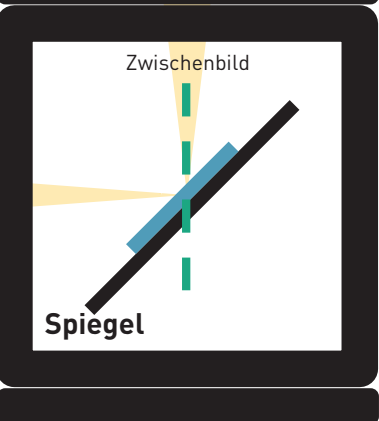
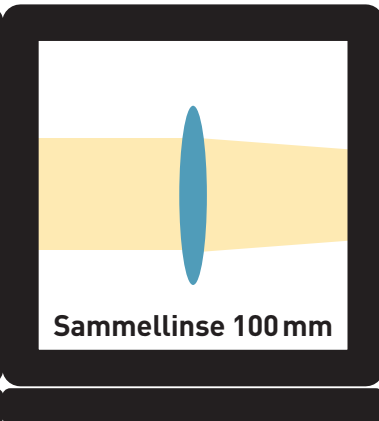
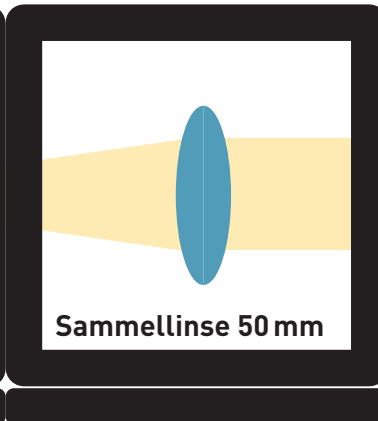
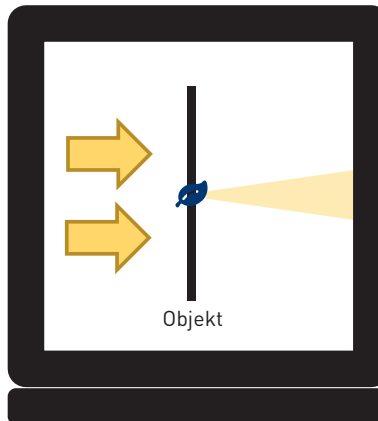


Beleuchtung

Objektiv

Tubulinse

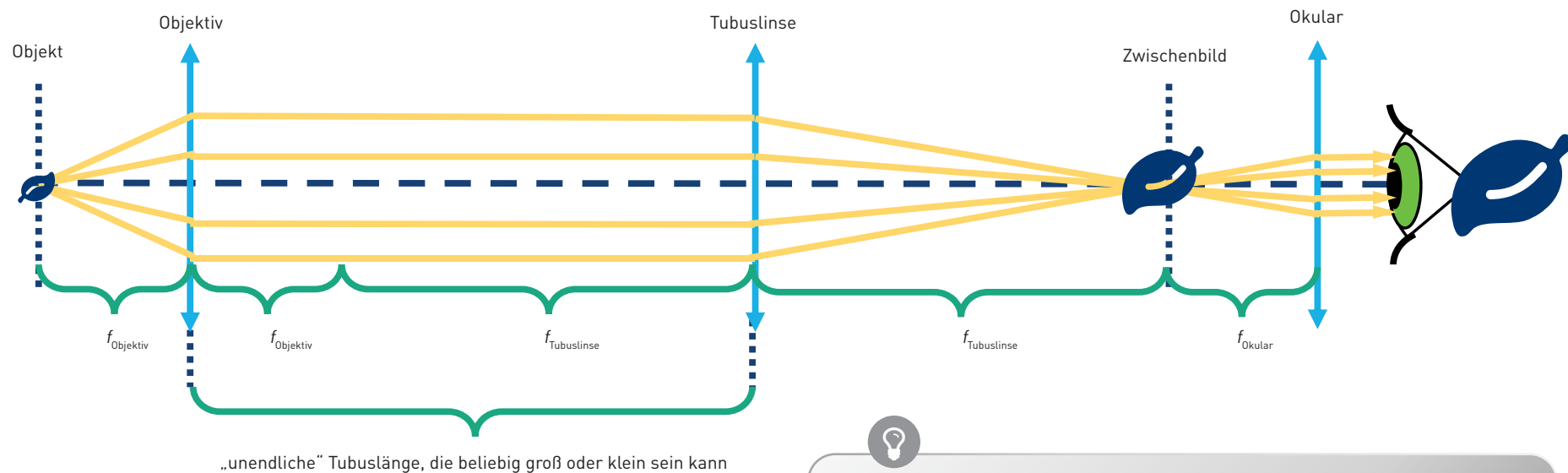
leer



Kannst du das mikroskopische Bild durch die Okularlinse mit dem Auge sehen? Welche Wirkung hat der Spiegel? Baue das Mikroskop ohne den Spiegel auf. Vergewissere dich, dass du nach wie vor zwei Leerräumen zwischen der Tubulinse und dem Okular hast. Was beobachtest du dann?

Dazu ist das Okular gut

Neuere Mikroskope sind mit einer sogenannten „Unendlich-Optik“ ausgestattet. In diesem Fall erzeugt das Objektiv kein reelles Zwischenbild. Das Licht verlässt das Objektiv als unendliche parallele Strahlen. Am Ende von dem „unendlichen“ Tubus befindet sich eine Tubuslinse. Diese erzeugt ein Zwischenbild, das dann wieder durch das Okular vergrößert wird.



Ein Filter kann dazu verwendet werden, die Helligkeit und Farbe des Bildes zu verändern.



Das Bild hinter dem Okular ist umgekehrt, seitenvertauscht, vergrößert und virtuell. Das virtuelle Bild kann man mit dem Auge sehen.

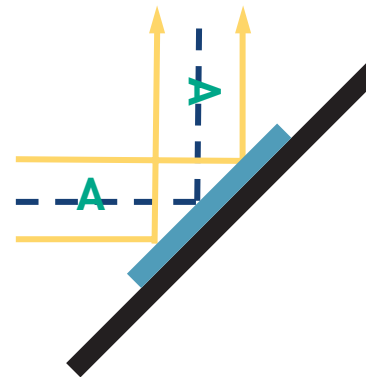
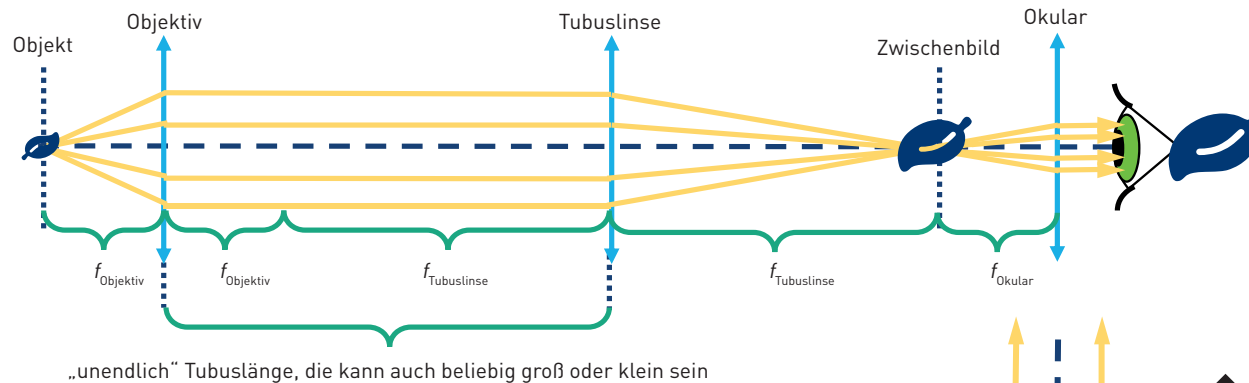
Diese Konfiguration ist in modernen Mikroskopen sehr nützlich, da zusätzliche Komponenten wie Filter zwischen Objektiv und Tubuslinse platziert werden können, ohne den optischen Pfad zu beeinträchtigen.

Dazu ist das Okular gut

Neuere Mikroskope sind mit einer sogenannten „Unendlichoptik“ ausgestattet. In diesem Fall erzeugt das Objektiv kein reelles Zwischenbild. Das Licht verlässt das Objektiv als unendliche parallele Strahlen. Am Ende von dem „unendlichen“ Tubus befindet sich eine Tubuslinse. Diese erzeugt ein Zwischenbild, das dann wieder durch das Okular vergrößert wird.



Was ist die Vergrößerung nach dem Okular?



Gesamtvergrößerung

$$V = \frac{f_{Tubuslinse}}{f_{Objektiv}} \times \frac{250 \text{ mm}}{f_{Okular}}$$



Ein Okular ist eigentlich nur eine Linse, die das Zwischenbild vergrößert. Es bildet das virtuelle Bild so ab, dass du es mit dem Auge betrachten kannst.



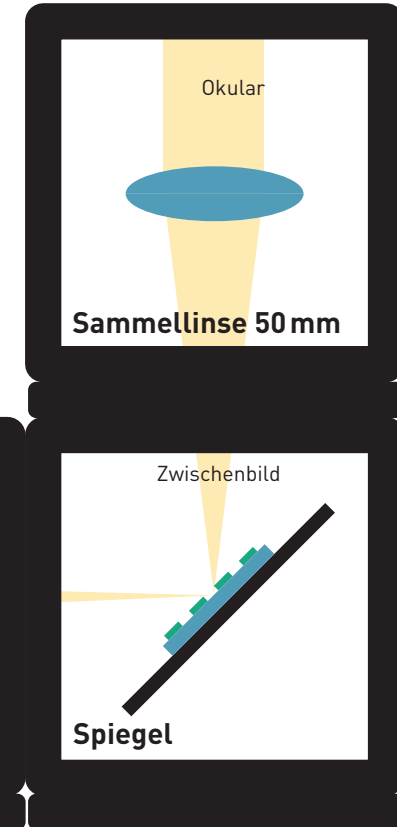
Mit dem Spiegel kannst du nicht nur dich selbst sehen, sondern auch das einfallende Licht in eine beliebige Richtung reflektieren. So kannst du den optischen Weg falten und die Arbeit damit angenehmer gestalten. Der Spiegel hat keinen Einfluss auf die Vergrößerung, aber er dreht das Bild in eine Richtung.

Lichtmikroskop mit „Endlich-Optik“

Stell' die Würfel auf die Positionen, wie unten im Diagramm gezeigt und schaue durch das Okular.



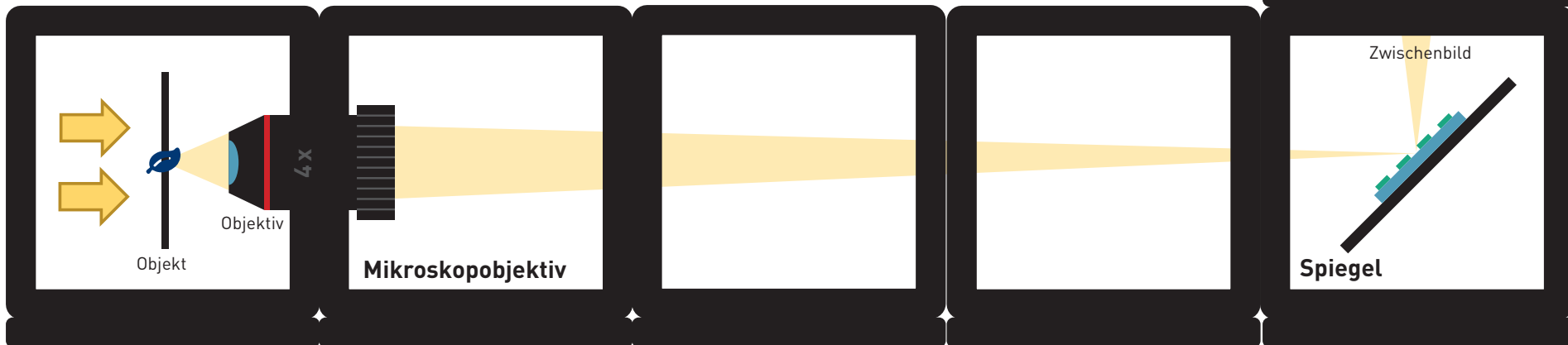
Bau' das Mikroskop wie ein Sandwich indem du eine zweite Schicht mittels Grundplatte hinzufügst. Schau' von oben durch das Okular.



Beleuchtung

leer

leer



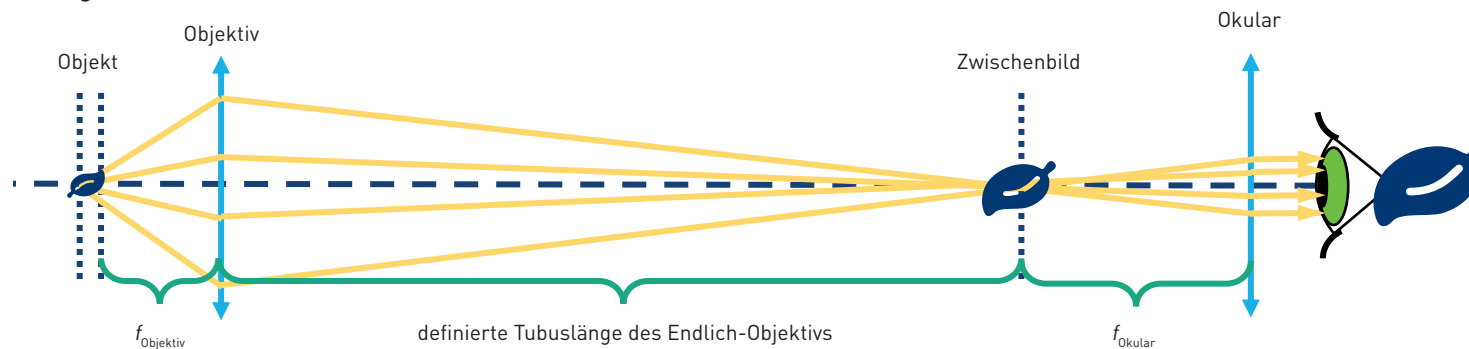
Siehst du das Bild wie bisher durch das Okular? Kannst du das echte Zwischenbild auch mit einem Blatt Papier finden?



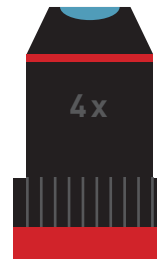
Drehe das kleine Zahnrad des Objektivhalters. Damit bewegst bzw. fokussierst du das Objektiv. Wenn es nicht weiter geht, kannst du auch das Objektiv in dem Halter verschieben.

„Endlich-Optik“ versus „Unendlich-Optik“

Die Objektive von älteren oder kleineren Mikroskopen sind häufig so genannte Endlich-Objektive. Sie verhalten sich wie eine Linse mit äußerst kurzer Brennweite und erzeugen ein Zwischenbild hinter dem Objektiv mit einer Bildweite die sich durch die Tubuslänge definiert. Die Tubuslänge ist aufgedruckt und entspricht bei unserem Objektiv 160 mm. Dort entsteht das reelle Zwischenbild und wird durch die Okularoptik vergrößert.



Mikroskope haben die Möglichkeit, das Objekt entweder durch Bewegen des Objekts oder des Objektivs zu fokussieren bzw. scharfzustellen. Hier verschieben wir den Objektivhalter einfach von Hand. Wir passen die Abstände zwischen den Komponenten an, um ein scharfes Bild zu sehen.



„Endlich-Optik“ versus „Unendlich-Optik“



Was ist die Vergrößerung des Zwischenbildes? Und was ist die Vergrößerung nach dem Okular?



Objektivvergrößerung

$$V = 4$$

wie darauf geschrieben



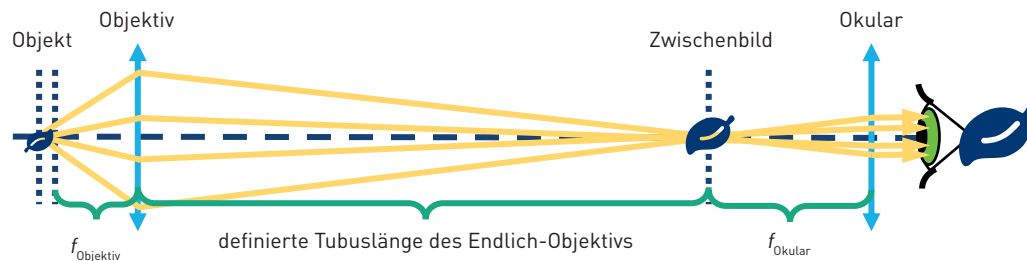
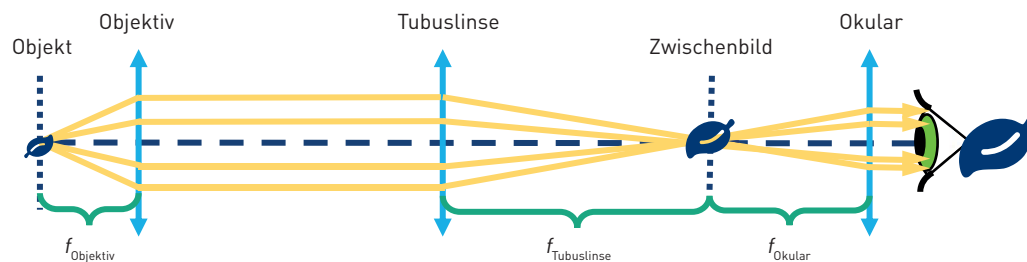
Okularvergrößerung

$$V = \frac{250 \text{ mm}}{f_{\text{Okular}}}$$



Gesamtvergrößerung

$$V = V_{\text{Objektiv}} \times V_{\text{Okular}}$$



Das Bild ist größer als mit dem Unendlich-Mikroskop. Die Vergrößerung des Objektivs beträgt hier 4x. Wenn du die Vergrößerung mit dem vorherigen Mikroskop berechnet hast, überrascht dich das sicherlich nicht.

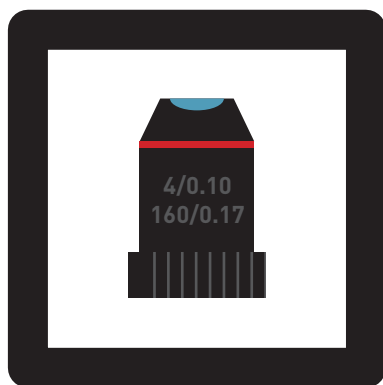


Das Zwischenbild wird jetzt nur noch durch das Objektiv gebildet und liegt 160 mm dahinter. Wir werden im nächsten Schritt herausfinden, warum.

Objektiv und Okular



Schau' auf das Objektiv! Was ist da drin? Was steht darauf geschrieben?



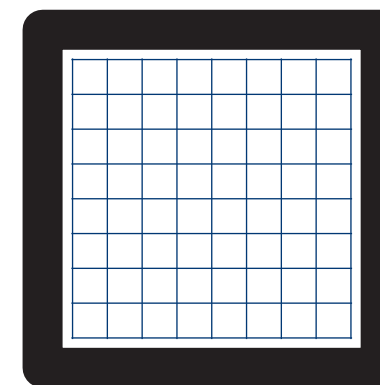
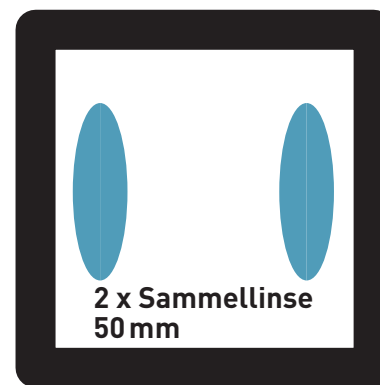
Schau' durch die 50-mm-Linse und dann durch das Objektiv auf den kleinen Text.



Welche von den Linsen vergrößert stärker? Was steht dort geschrieben?



Öffne die Würfel mit den 50-mm-Linsen. Platziere nun beide 50-mm-Linsen in einem Würfel, sodass die „Bäuche“ der Linsen aufeinander zeigen.



Schau' durch die einzelne 50-mm-Linse und dann durch die Doppellinse auf das Gitter.



Wie ändert sich die Vergrößerung und das Sichtfeld?

Das ist das Objektiv

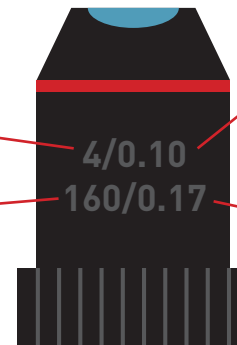
Ein Objektiv ist ein optisches System, das eine vergrößerte Abbildung eines Gegenstands erzeugt. Die verschiedenen auf dem Objektiv abgedruckten Zahlen haben verschiedene Bedeutungen:

Vergößerung:

Gängige Vergrößerungen sind 4x, 10x, 40x, 100x.

Tubuslänge:

∞ steht für unendlich, 160 steht für 160 mm und ist die am häufigsten verwendete Tubuslänge nach DIN



Numerische Apertur:

Sie bestimmt die Fähigkeit, Licht aufzusammeln und somit die optische Auflösung.

Deckglaskorrektur :

Manchmal wird ein Deckglas verwendet, um die Probe zu versiegeln. Ein Objektiv muss für diese Dicke (0,17 mm) korrigiert werden.



Das 4x Objektiv hat nur eine Linse drin. Die Objektive mit stärkerer Vergrößerung sind ganze Linsensysteme.



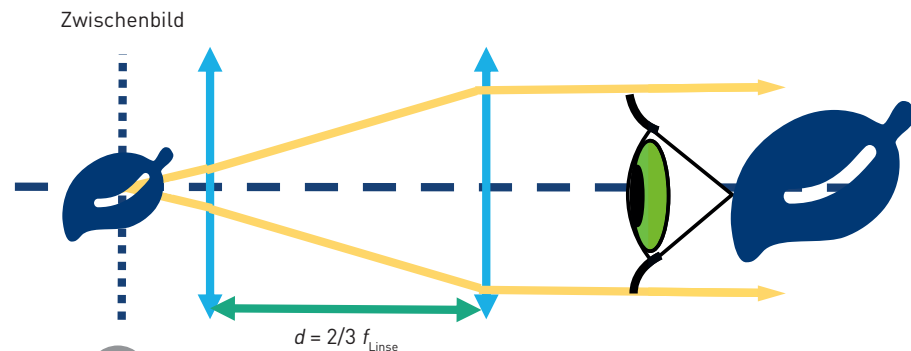
Das Objektiv ist auch eine Sammellinse mit kurzer Brennweite. Das 4x Objektiv hat eine Brennweite von $f=32$ mm. Wenn es als Lupe verwendet wird, hat es eine höhere Vergrößerung als das 40-mm-Objektiv. Das Sichtfeld ist scharf, aber klein.

Das ist das Okular

Ein Okular ist eigentlich eine Lupe, da es das Zwischenbild vergrößert. Das Okular, was wir hier verwenden, ist ein sogenanntes Ramsden-Okular. Eine einzelne Linse kann auch als Okular benutzt werden. Allerdings ist bei dem, aus einem Linsensystem bestehenden, Ramsden-Okular das Sichtfeld besser, weil es weniger Fehler am Rand des Sichtfelds erzeugt. Das Ramsden-Okular besteht aus zwei Linsen mit der gleichen Brennweite. Seine Brennweite beträgt $f_{\text{Ramsden-Okular}} = \frac{3}{4} f_{\text{Linse}}$



Was ist die Vergrößerung des Ramsden-Okulars? $V = \frac{250 \text{ mm}}{\frac{3}{4} f_{\text{Linse}}}$



Jedes Okular hat eine so genannte Ramsden-Scheibe, das ist der kleinste Durchmesser des Lichtstrahls, der aus dem Mikroskop durch das Okular austritt.



Der Abbildungsmaßstab ist bei kurzen Objektabständen höher als bei einem einzelnen 50-mm-Objektiv.



Das Sichtfeld ist größer und das Bild sieht mit dem Ramsden-Okular klarer aus.

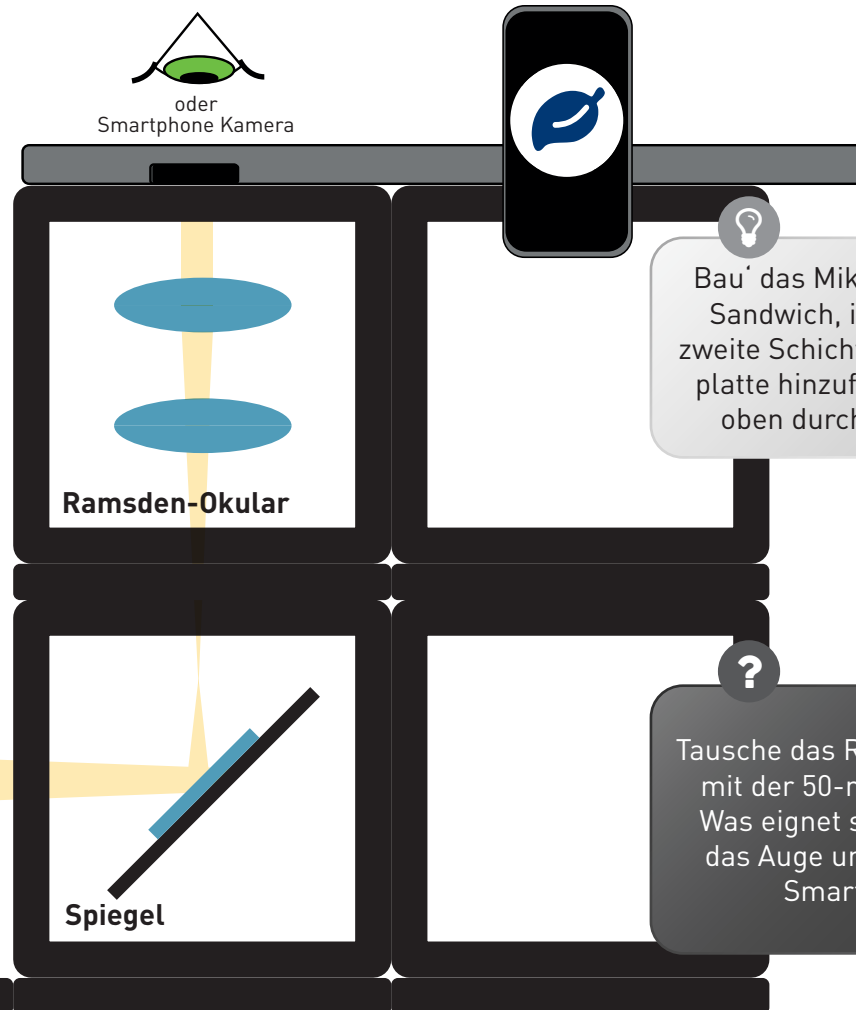
Beleuchtung

Smartphone Mikroskop

Baue das Smartphone Mikroskop wie dargestellt. Nutze zwei beliebige Würfel, um das Smartphone sicher zu platzieren.



oder
Smartphone Kamera



💡
Bau' das Mikroskop wie ein Sandwich, indem du eine zweite Schicht mittels Grundplatte hinzufügt. Schau von oben durch das Okular.

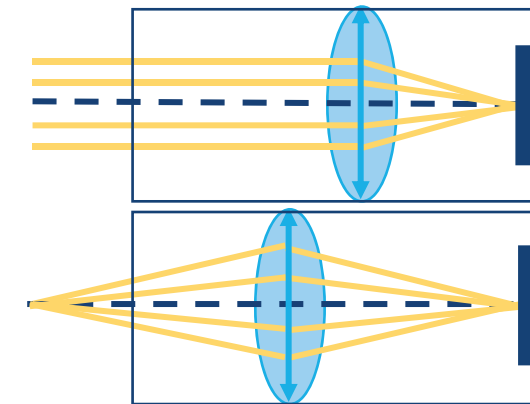
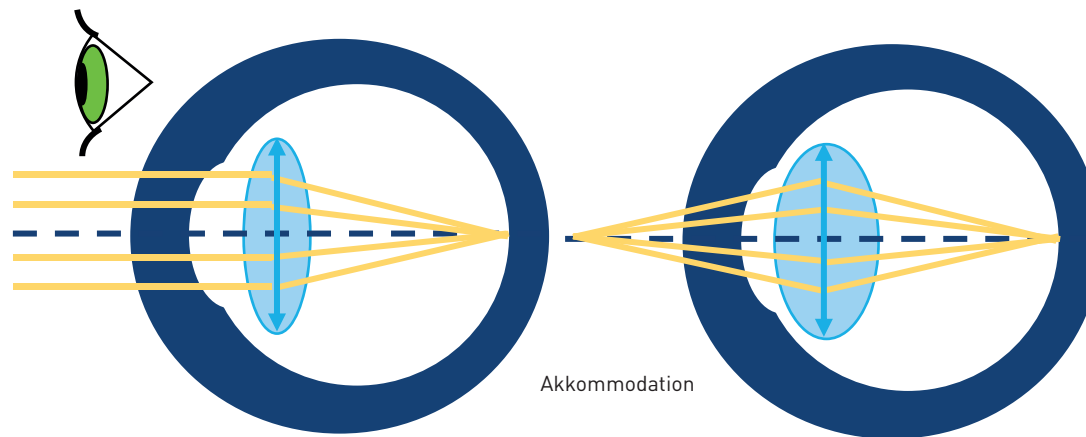
❓
Tausche das Ramsden-Okular mit der 50-mm-Linse aus. Was eignet sich besser für das Auge und was für das Smartphone?

Besser mit Smartphone oder Auge?

Die Smartphone Kamera hat eine Linse mit sehr kurzer Brennweite, da diese in das dünne Smartphone passen muss. Die Linse erzeugt dann ein Bild auf dem Kamera-Sensor, dessen Eigenschaften dem menschlichen Auge ähneln.



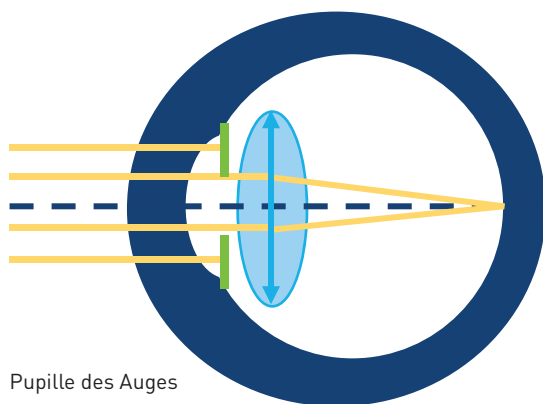
Das Auge kann die Objekte sowohl aus der Ferne als auch aus der Nähe abbilden. Diese Eigenschaft heißt Akkommodation. Die Smartphone-Kamera kann das auch, es wird allerdings als Autofokus bezeichnet. Es beschreibt die Fähigkeit, Objekte in unterschiedlichen Entfernungen scharf auf dem Sensor abzubilden.



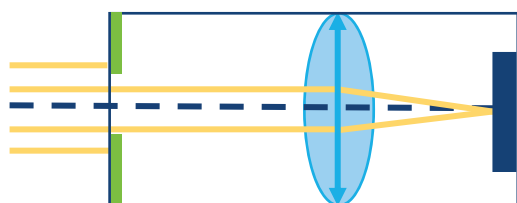
Das Bild aus dem Okular kommt in parallelen Strahlen, als käme es aus dem Unendlichen. Es wurde mit einem entspannten Auge (Blick in die Ferne) oder mit einer auf Unendlich fokussierten Kamera beobachtet.

Besser mit Smartphone oder Auge?

Um das Bild des Mikroskops sehen zu können, muss die Pupille – also die „Blende“, die den Einfall des Lichts begrenzt, mit der Ramsden-Scheibe des Okulars übereinstimmen. Die Pupille des Auges ist in dessen Inneren fixiert und kann nicht näher an das Okular herangeholt werden. Die Pupille der Smartphone-Kamera ist hingegen sehr nahe an der Oberfläche des Handys. Wegen dieses Unterschieds braucht man eine unterschiedliche Entfernung zum Okular für das Auge und die Kamera.



Pupille des Auges



Pupille der Kamera



Was ist die Vergrößerung dieses Mikroskops?
Formel zur Berechnung der Vergrößerung

$$V = V_{\text{Objektiv}} \times V_{\text{Ramsden-Okular}}$$



Beim Ramsden-Okular ist die Ramsden-Scheibe näher am Würfel und hat einen kleineren Durchmesser, was für die Smartphone-Kamera gut funktioniert.



Die Ramsden-Scheibe der einzelnen 50 mm-Linse hat einen größeren Durchmesser und ist daher für die Beobachtung der Probe mit dem Auge bequemer. Durch das Okular sieht es so aus, als ob das Bild auf dem Spiegel darunter liegt. Die 50 mm-Objektive haben einen großen Durchmesser, so dass bei der Verwendung eines einzigen Objektivs als Okular das Sichtfeld durch die Größe der Spiegel eingeschränkt wird.

Berechnungsergebnisse

Lupe

$$V_L = \frac{250 \text{ mm}}{50 \text{ mm}} = 5$$

Projektor

$$V_1 = \frac{300 \text{ mm}}{60 \text{ mm}} = 5$$

$$V_2 = \frac{217 \text{ mm}}{65 \text{ mm}} = 3,33$$

$$V_3 = \frac{175 \text{ mm}}{70 \text{ mm}} = 2,5$$

Galilei-Fernrohr

$$V_{GF} = \frac{100 \text{ mm}}{50 \text{ mm}} = 2$$

Kepler-Fernrohr

$$V_{KF} = \frac{100 \text{ mm}}{50 \text{ mm}} = 2$$

„Unendlich“-Mikroskop

$$V_{UM} = \frac{100 \text{ mm}}{50 \text{ mm}} = 2$$

„Unendlich“-Mikroskop mit Okular

$$V_{UMO} = \frac{100 \text{ mm}}{50 \text{ mm}} \cdot \frac{250 \text{ mm}}{50 \text{ mm}} = 10$$

„Endlich“-Mikroskop - Zwischenbild

$$V_{EMZ} = 4$$

„Endlich“-Mikroskop - Gesamtvergrößerung

$$V_{EMG} = 4 \cdot \frac{250 \text{ mm}}{50 \text{ mm}} = 20$$

Ramsden-Okular

$$V_{RO} = \frac{250 \text{ mm}}{\frac{3}{4} 50 \text{ mm}} = 6,66$$

Smartphone Mikroskop mit Ramsden-Okular

$$V_{SM} = 4 \cdot \frac{250 \text{ mm}}{\frac{3}{4} 50 \text{ mm}} = 26,66$$

Glossar

Lichtstrahl

Ein Pfeil oder eine Linie, die die Richtung des Lichts anzeigt; Wenn nicht anders gesagt, kommt das Licht in den Schemata immer von der linken Seite.

Linse

Ein transparenter lichtbrechender Körper z. B. aus Glas oder Plastik

Dünne Linse

Ein Modell einer Linse, das davon ausgeht, dass sie kein Volumen hat

Sammellinse

Eine Linse, die das einfallende Licht konvergiert (sammelt)

Zerstreuungslinse

Eine Linse, die das einfallende Licht auffächert

Brennpunkt F (Objektbrennpunkt), F' (Bildbrennpunkt)

Ein Punkt, an dem das Licht gebündelt wird (Sammellinse) oder von dem es auseinander zu laufen scheint (Zerstreuungslinse)

Brennweite f

Der Abstand zwischen dem Brennpunkt und der dünnen Linse

Brennebene

Eine Ebene parallel zur dünnen Linse, die durch den Brennpunkt verläuft

Optische Achse

Das Grundgerüst für jede optische Skizze; sie verläuft durch die Mitte der Linse und steht senkrecht zur Linsenebene

Virtuelles Bild

Ein durch eine Linse oder ein optisches System erzeugtes Bild, das von einem menschlichen Auge durch das System betrachtet werden kann

Reelles Bild

Ein durch eine Linse oder ein optisches System erzeugtes Bild, das auf einem Bildschirm hinter dem System betrachtet werden kann

Vergrößerung

Ein Verhältnis der Bildgröße und der Objektgröße (für ein reales Bild); ein Verhältnis des beobachteten Bildes und der Objektgröße (für ein virtuelles Bild)

Gegenstand

Ein Objekt, das wir mit der Linse abbilden wollen; die Größe des Objekts ist G

Entfernung g des Gegenstands

Der Abstand zwischen dem Objekt und der dünnen Linse

Bild

Eine Abbildung des Gegenstands; Die Größe des Bildes ist B .

Entfernung (b) des Bildes

Der Abstand zwischen dem Bild (real oder virtuell) und der dünnen Linse

Objektseite

Seite in Bezug auf die Linse, auf den sich das Objekt (Gegenstand) befindet; links in den Schemata

Bildseite

Seite in Bezug auf die Linse, auf der das reelle Bild entsteht; Das virtuelle Bild befindet sich auf der gleichen Seite wie das Objekt.

Mittelpunktstrahl

Mittelpunktstrahlen durchlaufen die dünne Linse unverändert.

Parallelstrahlen

Alle Strahlen, die parallel zur optischen Achse laufen, werden durch die Linse so gebrochen, dass sie sich in dem Brennpunkt treffen. Als hellster Punkt direkt hinter der Linse findet sich dieser nur bei Sammellinsen.

Brennpunktstrahlen

Alle Strahlen, die durch einen Brennpunkt verlaufen oder aus dem Brennpunkt kommen, werden durch die Linse so gebrochen, dass sie hinter der Linse parallel zur optischen Achse verlaufen.

Beleuchtung

In der Mikroskopie brauchst du eine Beleuchtungsquelle, um das Objekt sehen zu können. Das kann z. B. eine Taschenlampe oder die Reflektion von der Sonne sein.

Lupe (auch Vergrößerungsglas oder Brennglas)

Das einfachste optische Gerät, das das Objekt für das menschliche Auge vergrößert

Fernrohr (auch Linsenfernrohr oder Refraktor)

Ein optisches Instrument, bei dessen Nutzung entfernte Objekte um ein Vielfaches näher oder größer erscheinen

Objektiv

Ein optisches System, das eine reelle optische Abbildung eines Gegenstandes erzeugt

Okular

Der augenseitige Teil eines optischen Systems

Lichtmikroskop

Ein Mikroskop, das stark vergrößerte Bilder von kleinen Strukturen oder Objekten mit Hilfe von Licht erzeugt

Tubeulinse

Eine Linse, die nach dem Unendlich-Optik-Objektiv aus den parallelen Lichtstrahlen ein reelles Zwischenbild erzeugt

Zwischenbild

Vergrößerndes Bild des Objekts, das vom Objektiv erzeugt wird

Spiegel

Eine reflektierende Fläche, glatt genug, damit an ihr reflektiertes Licht ein Abbild erzeugen kann

Akkommodation des Auges

Eine dynamische Anpassung der Brechkraft des Auges; Sie führt dazu, dass Objekte verschiedener Entfernung scharf auf der Netzhaut abgebildet werden können.

Autofokus

Eine dynamische Anpassung der Brechkraft des Linsensystems einer Kamera



Impressum

Idee: Barbora Maršíková, Benedict Diederich, René Lachmann

Produktdesign: Barbora Maršíková, Benedict Diederich, René Lachmann

Layout: Katrin Uhlig

www.useetoo.org

Appendix C

Generic Lens Holder openSCAD code

In the following, the code for *20_Insert_Lens_holder_v3.scad*.

```

1 //Cube insert: Lens holder with clamp
2
3 /* [User Parameters] */
4 //Lens diameter - measure the diameter of your lens carefully
   and insert the value in millimetres. The holder can be used
   for lenses with a diameter from 9 mm to 42 mm.
5 lens_diameter = 25.4; //[9:0.01:42]
6 //Edge thickness - measure the thickness of your lens as close
   to the outer edge as possible.
7 lens_edge_thickness = 1.5; //[0.5:0.01:9]
8 // Which part would you like to print?
9 part = "first"; // [first:Both - Holder AND Clamp,second:Holder
   ONLY,third:Clamp ONLY]
10 // Write the focal length of the lens that you will put in this
   holder. Input: number in millimetres, no units, add '-' for
   a negative lens.
11 focal_length = "f";
12
13 /* [Hidden] */
14 $fn = 80;
15 eps = .002;
16 a = 49.8; //fit outer cube size
17 b = 33.6; //fit inner cube size
18 c = 6.28; //fit cube edge
19 d = 53.8; //fit inner cube diagonal
20 h = lens_edge_thickness < 4.1 ? 5 : 5+(lens_edge_thickness-3);
   //holder height
21 h1 = 3; //clamp rims height
22 t = 1.5; //clamp ring thickness
23 IM_offset = 0.2; //added after upgrading from v2 to v3/IM
24

```



```

25 print_part();
26
27 module print_part() { //choose part to print holder/clamp/both
28   if (part == "first") {
29     lens_holder();
30     lens_clamp();
31   } else if (part == "second") {
32     lens_holder();
33   } else if (part == "third") {
34     lens_clamp();
35   }
36 }
37
38 module lens_holder () {
39   difference(){
40     union() { //basic insert design
41       cube([a,b+2*IM_offset,h], center=true);
42       cube([b+2*IM_offset,a,h], center=true);
43       rotate(a=[0,0,45]){
44         cube([c,d+2*IM_offset,h], center=true);
45       }
46       rotate(a=[0,0,-45]){
47         cube([c,d+2*IM_offset,h], center=true);
48       }
49     }
50     union() {
51       cylinder(h+eps,d=lens_diameter-2, center = true); //
52       hole
53       translate([0,0,(h-lens_edge_thickness)/2]){
54         cylinder(lens_edge_thickness+eps,d=lens_diameter
55 +0.7, center = true); //rim to hold the lens
56       }
57       translate([0,-24,((h+h1-0.1)/2-2.45)]){ //focal length
58         inscription, ellipse fixing marks
59         linear_extrude(height = 2) text(focal_length, size
60 =5, font="Arial black:style=Regular",halign = "center",
61 spacing=1);
62         translate([(lens_diameter+2.9)/2+1,a/2-1,0]){cube
63 ([3,1,2+eps], center = true);}
64         translate([-1,(a+lens_diameter+2.9)/2+1,0]){cube
65 ([1,3,2+eps], center = true);}
66         translate([1,(a+lens_diameter+2.9)/2+1,0]){cube
67 ([1,3,2+eps], center = true);}
68       }
69     }
70   }
71 }

```

```

63     translate([0,0,(h+h1-0.1)/2]){ //rim for the clamp
64         scale([1,1.03,1])difference(){
65             cylinder(h1+0.1,d=lens_diameter+2.9, center =
66             true);
67             cylinder(h1+0.1+eps,d=lens_diameter+0.7, center
68             = true);
69         }
70     }
71 module lens_clamp() {
72     translate([a/2+lens_diameter/2+7,0,-(h-t)/2]){
73         scale([1,1.03,1])difference(){ //bottom ring
74             cylinder(t, d=lens_diameter+4.9, center = true);
75             cylinder(t+eps, d=lens_diameter-1, center = true);
76         }
77         translate([0,0,+(h1+t)/2]){
78             scale([1,1.03,1])difference(){ //outer rim
79                 cylinder(h1,d=lens_diameter+4.9, center = true);
80                 cylinder(h1+eps,d=lens_diameter+2.9, center =
81                 true);
82             }
83             scale([1,1.03,1])difference(){ //inner rim
84                 cylinder(h1,d=lens_diameter+0.5, center = true);
85                 cylinder(h1+eps,d=lens_diameter-1, center = true
86                 );
87             }
88             translate([(lens_diameter+4.9)/2,0,-t/2]){cylinder(t+h1
89             ,2,2,$fn=3);} //beak

```

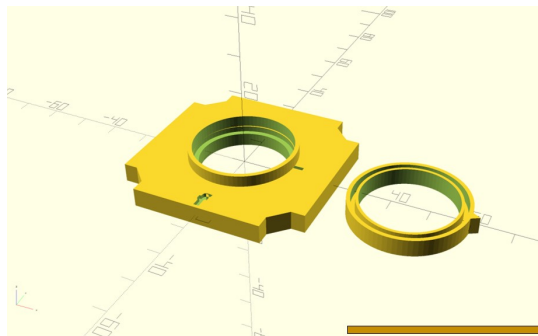


FIGURE C.1: Preview of code above rendered by the openSCAD. Scale bars: 50 mm.

Appendix D

MiniBOX product calculation

The complete and up-to-date BOM is available UC2 GitHub repository [7]. The documentation includes the *.stl and original design files of all 3D-printable components, lists of compatible external components, assembly and usage instructions.

Detailed product calculation of the MiniBOX versions compared in 4.1.2:

- **Table D.1:** Values used for the calculation of the production cost
- **Table D.2:** Fully 3D-printed MiniBOX
- **Table D.3:** MiniBOX with injection moulded cubes and 3D-printed inserts
- **Table D.3:** MiniBOX with injection moulded cubes and laser cut inserts

The calculation estimates the material and manufacturing costs based on the tested and accessible components and on the experience of the developers. The production is designed in a way that can be scaled, therefore producing a large number of MiniBOXes would decrease the costs and the time per one BOX. We calculated with the price of 1.47€ per lens, because for this we bought the 400 lenses for the GNDÄ conference workshop, although the advertised price is higher.

The calculation of the running costs of the 3D-printer and laser cutter are estimated considering that for the future UC2 company we would buy these devices and produce the parts using those. The printing and laser cutting cost of a third-party company would be significantly higher.

The following device and settings were used for the comparison of 3D-printing times:

- 3D-printer: Prusa i3 MK3S, Prusa Research a.s., Czech Republic
- Slicer software: PrusaSlicer
- Profile: 0.15 mm SPEED (layer height 0.15 mm)
- Filament: Prusament PLA
- Supports: None
- Infill: 20%

The following device and settings were used for the comparison of laser cutting times:

- Laser Machine: Epilog Helix 24, 75 W, Epilog Laser, Colorado, USA
- For cutting the 3 mm thick acrylic glass: speed = 24%, power = 100%, frequency = 5000 Hz.
- For cutting the PU foam: speed = 65%, power = 40%, frequency = 494 Hz.

	Price per unit	Source
3D printing material	30€/kg	[97]
Prusa i3 MK3S energy consumption	80 W/h	[98]
Prusa i3 MK3S estimated amortization	0.8€/h	Based on the machine's price [99] and lifetime of the nozzle [98]
Electricity price (Jena)	0.5€/kWh	[100]
Prusa i3 MK3S running costs	1.2€/h	Calculated from the above lines
Epilog Helix laser cutter estimated amortization	2.7€/h	Based on the machine's price [101] and advertised lifetime of the laser tube [102]
Epilog Helix laser cutter running costs	3.4€/h	[103]
Student assistant (HiWi) assembling the MiniBOX	30€/h	Common in the area

TABLE D.1: Values used for the calculation of the production cost. The equipment and maintenance costs are roughly estimated in the amortization.

	Price per unit /€	Quantity	Price /€
External parts			
Lens double-convex 50 mm	1.47	2	2.94
Lens double-convex 100 mm	1.47	1	1.47
Lens double-concave 50 mm	1.47	1	1.47
Adhesive mirror 30 × 30 mm ²	0.08	2	0.16
Microscope objective 4×	10.11	1	10.11
M3x30 screw	0.03	1	0.03
M3x8 screw	0.03	4	0.12
M3 nut	0.03	1	0.03
M3x12 screw	0.03	64	0.15
M5x8	0.03	48	1.44
Ballmagnets	0.38	32	12.16
Box	2.82	1	2.82
Total		158	32.89
Produced parts (3DP)	30€/kg	0.260 kg	7.80
20_Cube_insert_Sample_holder_v3		1	
20_Cube_Insert_Sample_clamp_v3		1	
20_Cube_Insert_Mirror_Holder_wLogo_v3		2	
20_Insert_Lens_holder_v3 (Convex 50)		4	
20_Insert_Lens_holder_v3 (Convex 100)		2	
20_Insert_Lens_holder_v3 (Concave 50)		2	
20_focus_inlet_linearflexure_mechanical_v3		1	
20_focus_inlet_objective_mount_v8_v3		1	
20_gear_v3		1	
30_Smartphone_Holder_v3		1	
10_Base_puzzle_v3		8	
10_Cube_1x1_v3		8	
10_Lid_1x1_v3		8	
Total		40	7.80
Material costs			40.69
Manufacturing		Time	
3D printing		34h55min	41.90
Assembly and preparation time		03h30min	105
Total		38h25min	146.90
	Manu- facturing time	Amount of assembly parts	Total costs /€
	38h25min	198	187.59

TABLE D.2: Fully 3D-printed MiniBOX. The cube and the lid are considered two parts, as they require to be assembled using screws. Each lens holder contains the insert and the clamp, therefore one lens holder insert equals two components.

	Price per unit /€	Quantity	Price /€
External parts			
IM cube + baseplate puzzle	5.00	8 + 8	40.00
Lens double-convex 50 mm	1.47	2	2.94
Lens double-convex 100 mm	1.47	1	1.47
Lens double-concave 50 mm	1.47	1	1.47
Adhesive mirror 30 × 30 mm ²	0,08	2	0.16
Microscope objective 4×	10.11	1	10.11
M3x30 screw	0.03	1	0.03
M3x8 screw	0.03	4	0.12
M3 nut	0.03	1	0.03
Box	2.82	1	2.82
Total		30	59.14
Produced parts (3DP)	30€/kg	0.115 kg	3.45
20_Cube_insert_Sample_holder_v3		1	
20_Cube_Insert_Sample_clamp_v3		1	
20_Cube_Insert_Mirror_Holder_wLogo_v3		2	
20_Insert_Lens_holder_v3 (Convex 50)		4	
20_Insert_Lens_holder_v3 (Convex 100)		2	
20_Insert_Lens_holder_v3 (Concave 50)		2	
20_focus_inlet_linearflexure_mechanical_v3		1	
20_focus_inlet_objective_mount_v8_v3		1	
20_gear_v3		1	
30_Smartphone_Holder_v3		1	
Total		16	3.45
Material costs			62.59
Manufacturing		Time	
3D printing		11h55min	14.30
Assembly and preparation time		02h15min	67.5
Total		14h10min	81.80
	Manu- facturing time	Amount of assembly parts	Total costs /€
	14h10min	46	144.39

TABLE D.3: MiniBOX with injection moulded cubes and 3D-printed inserts. The cube is considered a single part, as there is no assembly required (it is part of the user experience). Each lens holder contains the insert and the clamp, therefore one lens holder insert equals two components.

	Price per unit /€	Quantity	Price /€
External parts			
IM cube + baseplate puzzle	5.00	8 + 8	40.00
Lens double-convex 50 mm	1.47	2	2.94
Lens double-convex 100 mm	1.47	1	1.47
Lens double-concave 50 mm	1.47	1	1.47
Adhesive mirror 30 × 30 mm ²	0.08	2	0.16
Microscope objective 4×	10.11	1	10.11
M3x18 screw	0.03	3	0.09
M3x16 screw	0.03	8	0.24
M3x14 screw	0.03	6	0.18
M3x12 screw	0.03	5	0,15
M3 nut	0.03	22	0.66
Spring	1.55	2	3.10
Box	2.82	1	2.82
Total		70	63.38
Produced parts (LC, 3DP)			
LC_lens_holder_outer	0.2	4	0.80
LC_lens_holder_outer	0.2	2	0.40
LC_lens_holder_outer	0.2	2	0.40
LC_lens_holder_foam	0.02	4	0.08
LC_mirror_holder_back	0.2	2	0.30
LC_mirror_holder_front	0.1	2	0.12
LC_mirror_holder_mirror_frame	0.1	2	0.12
LC_mirror_holder_mirror_plate	0.2	2	0.30
LC_objective_holder	0.2	1	0.15
LC_sample_holder_insert	0.2	1	0.15
30_Smartphone_Holder_v3	0.6	1	0.60
3DP_sample_clip	0.04	1	0.04
Total		24	3.46
Material costs			66.84
Manufacturing		Time	
3D printing		00h15min	0.30
Laser cutter		00h30min	1.70
Assembly and preparation time		00h45min	22.5
Total		01h30min	24.50
	Manu- facturing	Amount of assembly parts	Total costs /€
	01h30min	94	91.34

TABLE D.4: MiniBOX with injection moulded cubes and laser cut inserts.

Appendix E

UC2 Demand Survey

Results of the UC2 Demand survey were collected between 07.05.2021 and 25.10.2021 using Google Forms. In addition of the five questions whose answers are shown in Fig. E.1 - E.5 we also provided the opportunity to freely indicate interest in any other part of the toolbox (new modules, collaboration on development of new applications, ...).

The introduction of the survey:

“ UC2 (You.See.Too.) is a general purpose modular toolbox for building optical projects and bridging methods and technologies to provide tailored solutions. Building a microscope using UC2 becomes as easy as building a Lego®house, since the toolbox relies on commercially obtainable components and 3D-printed building blocks. It is available online and fully open source, so that anyone can use it, reproduce it, and adapt it to their purposes. It is supported by detailed documentation and guidelines. Therefore, it provides an affordable and accessible tool for both education and research. ”

“ Maybe you were already asking us where you can buy a BOX, maybe you haven't heard about us yet. In any case, we appreciate that you take your time and answer the following questions to help us advance the project and offer the product for sale! ”

I am interested in using the toolbox for

75 responses

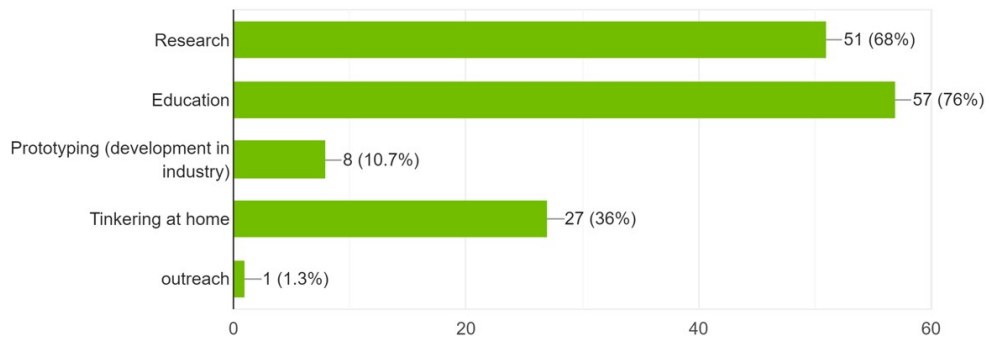


FIGURE E.1: Question 1: The aimed use of the toolbox.

Country, where I would buy and use the toolbox:

75 responses

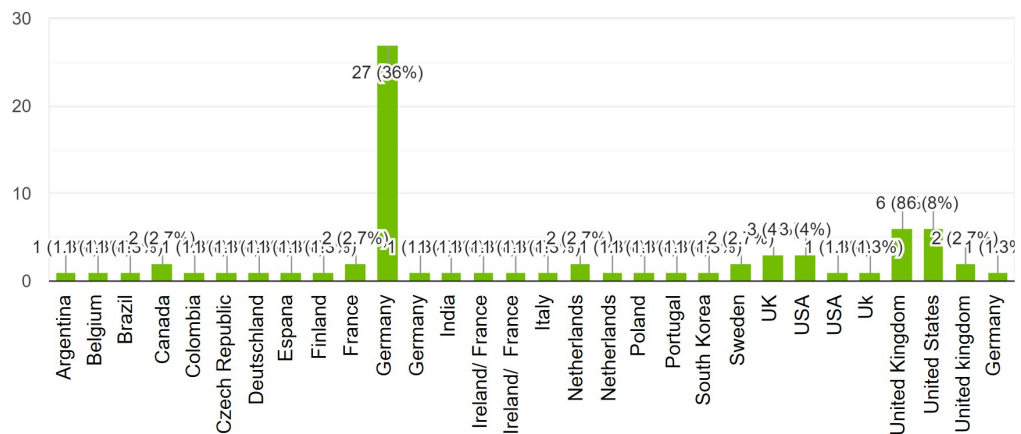


FIGURE E.2: Question 2: The location of using the toolbox.

I am interested in using the toolbox (more options are possible)

75 responses

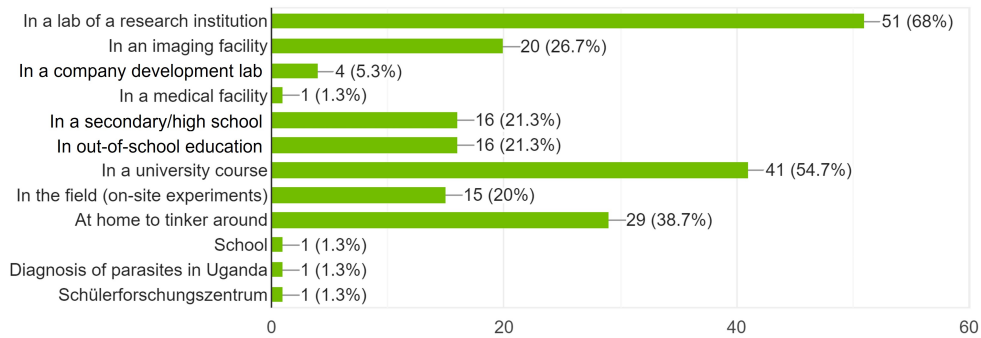


FIGURE E.3: Question 3: Specification of the aimed use of the toolbox.

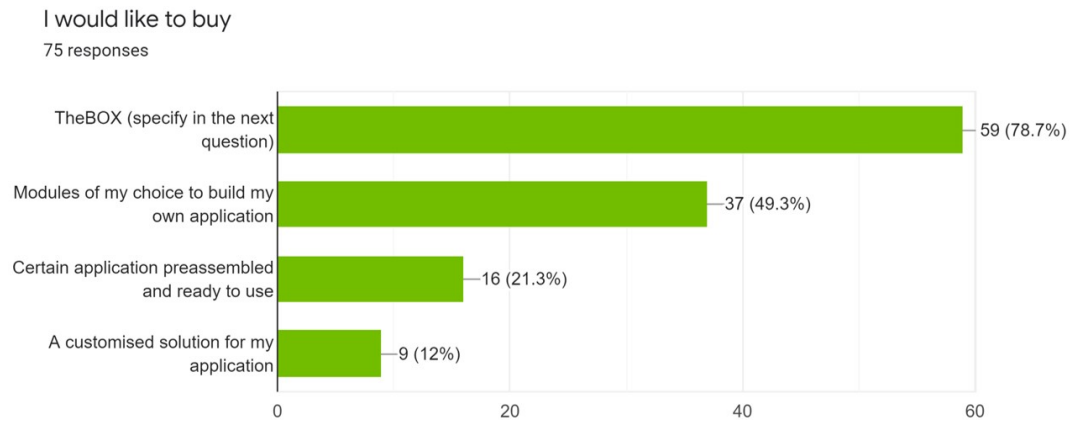


FIGURE E.4: Question 4: Preferred toolbox product.

I would be interested in purchasing the following BOXes:

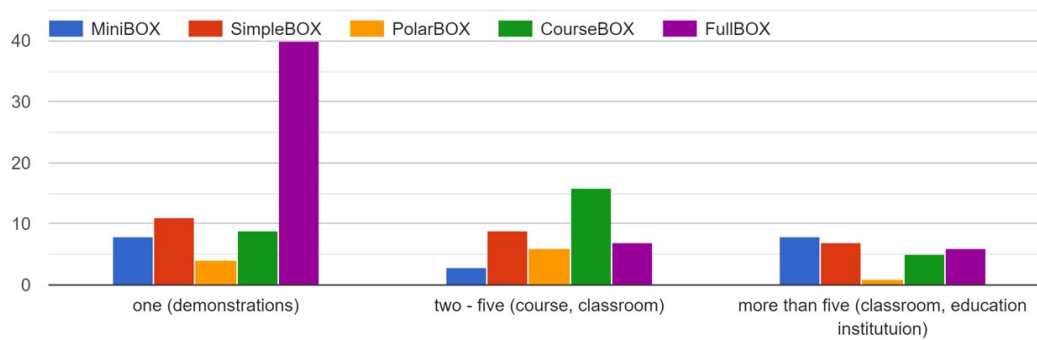


FIGURE E.5: Question 5: Preferred type of TheBOX.


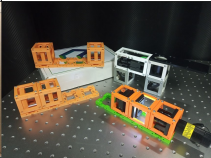
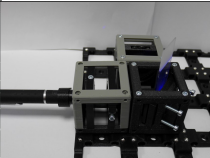
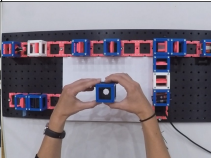
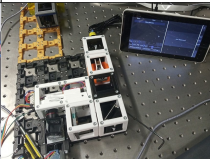
MiniBOX	SimpleBOX	PolarBOX	CourseBOX	FullBOX
8 cubes	11 cubes	9 cubes	18 cubes	16 cubes + extra inserts
9 experiments	9 experiments	7 experiments	6 experiments	12 experiments
Minimalistic, passive components, includes manual	More flexibility for the MiniBOX experiments	Demonstration of polarization effects of light	Abbe diffraction and microscope alignment hands-on	Motorized stages, programmable illumination, lab to-go
Projector, Telescopes, Smartphone microscope	MiniBOX experiments with an extra eyepiece – real microscopy imaging	Crossed polarizers, Brewster angle, Stress birefringence, Optical activity	Infinity optics, Köhler illumination, Abbe diffraction experiment	Incubator microscope, Light sheet microscope, In-line holography, All simple experiments
				

FIGURE E.6: The introduction of the BOXes for question 5.

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UC2-GIT references

Specified references to the UC2-GIT GitHub Repository in order of appearance:

Page	Commit	Description	Link
3	ef6066d	Current Repository	/UC2-GIT
3	ef6066d	Current Repository	/UC2-GIT
11	d6f3d34	Initial commit	/UC2-GIT
12	ef6066d	CAD; List of available modules	/UC2-GIT/CAD
12	ef6066d	APPLICATIONS; List of available ones	/UC2-GIT /APPLICATIONS
13	ef6066d	MDK; UC2 version history	/UC2-GIT/MDK
37	ef6066d	Modular Developer Kit chart	/UC2-GIT/MDK
56	ef6066d	3DP baseplate	/UC2-GIT/TheBOX/CAD /ASSEMBLY_Baseplate
61	ef6066d	Tutorials	/TUTORIALS
64	ef6066d	TheBOX, BOMs and instructions for each BOX in their respective folders	/UC2-GIT/TheBOX
65	ef6066d	CAD; List of available modules	/UC2-GIT/CAD
74	ef6066d	MiniBOX booklet	/UC2-GIT/TheBOX /SimpleBOX /DOCUMENTS /MiniBOX_booklet
76	fda3f15	CoreBOX	/UC2-GIT /TheBOX /CoreBOX
77	ef6066d	The Course BOX Alignment Procedure (Finite Optics)	/UC2-GIT/TheBOX /CourseBOX /ALIGNMENT_FinOptics
78	ef6066d	CourseBOX: Light Microscopy and Optical Alignment (Infinity Optics)	/UC2-GIT/TheBOX /CourseBOX /ALIGNMENT_InfOptics
83	ef6066d	Lightsheet Setup (Workshop) - Alignment of the optical path	/UC2-GIT /APPLICATIONS /APP_LIGHTSHEET_Workshop
83	ef6066d	Light sheet microscope - DIY (for the MAKE article)	/UC2-GIT /WORKSHOP /MAKE_LIGHT_SHEET
95	ef6066d	Current Repository	/UC2-GIT
109	ef6066d	Bill of Materials (Google Docs link)	/UC2-GIT
109	ef6066d	MiniBOX; Build me	/UC2-GIT/TheBOX /SimpleBOX /BUILD_ME

Specified references to the versions of the lens cube (section 3.1.1):

Figure	Commit	Description	Link
3.2a	184c049	The cage plates mounted in cubes v0, rendering of the Keplerian telescope.	/UC2-GIT/CAD /SIMPLE-Telescope
3.2b	a8a145e	The 3D-printed cage plated with a C-ring.	/UC2-GIT/CAD /CUBE_Lensholder
3.2c	a8a145e	Rendering of the spiral lens holder mountable on the rods of cubes v0.	/UC2-GIT/CAD /CUBE_Lensholder
3.3a	7dcd0f4	The spiral lens holder.	/UC2-GIT/CAD /ASSEMBLY_CUBE_Lens_v2
3.3b	afdf3e0	The first parametric holder using an O-ring.	/UC2-GIT/CAD /ASSEMBLY_CUBE_Lens_v2
3.4a	4bfc4ac	Parametric lens holder design with openSCAD. First version, assembled.	/UC2-GIT/CAD /ASSEMBLY_CUBE_Lens_v2/OPENS CAD
3.4b	fbf8474	Parametric lens holder design with openSCAD. First version, showing assembly principle.	/UC2-GIT/CAD /ASSEMBLY_CUBE_Lens_v2
3.4c	fbf8474	The holder for large lenses.	/UC2-GIT/CAD /ASSEMBLY_CUBE_Lens_v2
3.4d	ef6066d	The latest version of the generic 3D-printed holder.	/UC2-GIT/CAD /ASSEMBLY_CUBE_Lens

Specified references to the other modules from section 3.1):

Section	Commit	Description	Link
3.1.2	ef6066d	Circular aperture cube	/UC2-GIT/CAD /ASSEMBLY_CUBE_Aperture_Circular
3.1.3	ef6066d	Rectangular aperture cube	/UC2-GIT/CAD /ASSEMBLY_CUBE_Aperture_Rectangular
3.1.4	ef6066d	Mechanical Z-stage	/UC2-GIT/CAD /ASSEMBLY_CUBE_Z-STAGE_mechanical

Barbora Marsikova

Curriculum Vitae

PERSONAL DETAILS

Born on 28.06.1994
Born in Brno, Czech Republic
Mail marsikova.b@gmail.com

EDUCATION

Doctoral studies in Biophotonics/Engineering/Microscopy 2018 - Now
Friedrich-Schiller University and Leibniz-Institute of Photonic Technologies e. V., Jena, Germany

Topic: Modular Open-Source Toolbox for Optics Education (Dr. Ing.)

Master studies 2016 - 2018
Brno University of Technology, Brno, Czech Republic

Applied Sciences in Engineering, Precise Mechanics and Optics (Ing.), Master thesis: Coherence-gate assisted three-dimensional imaging by holographic microscope, Final exam on 20.06.2018, Final Grade: 1.0

Bachelor studies 2013 - 2016
Masaryk University, Brno, Czech Republic

Specializations in Health Science, Optics and Optometry (Bc.), Bachelor thesis: Bionic eye, Final exam on 02.06.2016, Final Grade: 1.0

Grammar school 2005 - 2013
Gymnázium Česká a Olympijských nadějí, Česká 64, České Budějovice, Czech Republic

79-41-K/81, Final exam on 24.05.2013 (Abitur), Final Grade: 1.0

WORK EXPERIENCE

Research assistant for digitized Photonics education 2022 - Now
Max Planck School of Photonics, Jena, Germany

Jena, den

.....
Barbora Marsikova